010292 (IPY-CARE)

IPY-CARE

Climate of the Arctic and its Role for Europe (CARE) – a European component of the International Polar Year

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PRIORITY [1.1.6.3]
[Sustainable Development, Global Change and Ecosystems]

D3-2 Science Plan

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Contents

Project Summary

The Arctic has over the last 2-3 decades warmed more than other regions of the world, and the sea ice cover has decreased in the order of 10% in the same period. Climate models furthermore indicate that anthropogenic global warming will be enhanced in the northern high latitudes due to complex feedback mechanisms in the atmosphere–ocean–ice system. At the end of this century, the Arctic Ocean is predicted to be "a blue ocean" during summer time. The Arctic may therefore encounter the most rapid and dramatic changes during the 21st century, with significant consequences for environment and human activities.

The IPY-CARE Science Plan has been developed by the IPY-CARE Steering Committee and participants and funded through an EU Specific Support Action. The overall objective is:

To explore, quantify and model Arctic climate change, its interaction with the climate in lower latitudes and its impact on Arctic marine ecosystem, and to assess the socio-economic consequences for Europe

Expert groups were established for the following six main Workpackages which represent the main components of the Science Plan: **WP1:** Processes determining Arctic climate variability and changes; **WP2:** Marine biological processes in response to climate change; **WP3:** Air-sea-ice mesoscale processes and climate variability; **WP4:** Past climate variability; **WP5:** Remote sensing and new technology for climate data provision, and **WP6:** Assessment of Arctic climate change impacts on climate in Europe including the Mediterranean area and socio-economic consequences for Europe.

The expert groups have prepared the contribution to each of the Workpackages. A main part of this activity was the organisation of the IPY-CARE conference at Alfred Wegener Institute in Bremerhaven 12 – 14 October 2005.

The activities planned for IPY-CARE include the following components: (1) Collection, analysis and harmonisation of historical and new modern data sets; (2) Development of new *in situ* observing systems for the ice-covered Arctic Ocean; (3) planning, coordination and implementation of Arctic field experiments; (4) Use of satellite remote sensing observing systems and analysis of data from these systems; (5) Global climate models with improved parameterisation and validation; (6) Demonstration and use of new ice and underwater buoy technology including use of hovercraft for innovative data collection; (7) Exchange programmes for scientists and training for students; (8) Co-ordinated promotion and outreach activities; (9) Technology development and scientific service transferred to SMEs; and (10) Modelling and prediction of the Arctic climate.

IPY-CARE will require large and multi-disciplinary resources that can only be mobilized by a joint effort of a broad consortium, which includes all the major polar research institutions and groups on international level. IPY-CARE will build up promotion and outreach activities to raise the awareness of the importance of the Arctic for global climate, resource exploitation, transport and environmental vulnerability. Furthermore, IPY-CARE will develop education and training programs in the area of Arctic climate research for young scientists in Europe.

Project objectives and state-of-the-art

Objectives

The overall objective is:

To explore, quantify and model Arctic climate change, its interaction with the climate in lower latitudes and its impact on Arctic marine ecosystem, and to assess the socio-economic consequences for Europe

with the following six specific objectives:

1. To determine the processes responsible for the past and present variability and changes in the Arctic climate system and to improve their representation in regional and global climate models
2. To understand the degree to which recent variability and changes in the Arctic climate system, e.g., shrinking sea-ice cover, thawing permafrost and increased methane emission, are of natural or anthropogenic origin
3. To understand and quantify the response of marine biological processes to climate change and their effects on Arctic marine ecosystems and the air–sea CO_2 fluxes and to improve their representation in ecosystem models and inclusion in global climate models
4. To quantify the Arctic freshwater budget and its linkages to the global thermohaline circulation (THC) and climate, and to assess its potential in causing rapid climate change, sea-level change and sequestration of CO_2
5. To improve capabilities to predict Arctic climate on decadal and longer time scales and design optimal components of an integrated monitoring and forecasting system
6. To assess the impact of climate change in the Arctic on the THC, marine ecosystems and fisheries, transportation, offshore industry and oil and gas production, coastal infrastructures, and on climate in Europe

State of art and rationale

The Arctic Ocean was a *mare incognito* when Fridtjof Nansen in 1893 let the purpose-built vessel *Fram* freeze into the Arctic sea ice and drifted across the Arctic Ocean (Nansen, 1897). The inhostile, dangerous and dynamic Arctic environment and the remote location have been prohibitive for gaining deep knowledge of the climate of the region. The current understanding is nevertheless that the Arctic is (i) vulnerable to human-induced global warming, (ii) shows large natural climate variability, and (iii) holds wildcards that can influence the global climate system in dramatic ways (Bobylev *et al.*, 2003; Johannessen *et al.*, 2004; ACIA, 2005).

Instrumental observations, particularly from the former Soviet Union, show a pronounced warming in the Arctic between 1920 and into the 1940s, known as the early 20th-century warming (Bengtsson *et al.*, 2004) and a marked cooling in the following decades, with corresponding changes in the sea ice cover (Johannessen *et al.*, 2004) (Fig. 1). Recent synthesis reviews (Serreze *et al.*, 2000; SEARCH, 2001; Moritz *et al.*, 2002) based on available observational evidence provide a reasonably coherent portrait of Arctic climate change, indicating that the last 2-3 decades have experienced unusual warming over northern Eurasia and North America, reduced Arctic sea ice (Johannessen *et al.*, 1999b; Rothrock *et al.*, 1999; Serreze *et al.*, 2003; Yu *et al.*, 2004; Kvingedal, 2005; Lindsay and Zhang, 2005) marked changes in Arctic Ocean hydrography (Morison *et al.*, 1998; Dickson, 1999; Swift *et al.*, 2005), increased runoff into the Arctic (Peterson *et al.*, 2002), increased tree growth in northern Eurasia (Mynemi *et al.*, 1997), and reduced tundra areas (Serreze *et al.*, 2000; Wang and You, 2004) and thawing permafrost.

The Arctic glaciers have, in general, retreated over the same period (Dyurgerov and Meier, 2000; Rignot *et al.*, 2004), whereas less is known about the Greenland ice sheet, one of the wildcards of the climate system. The latter has been the subject of increased attention for two important reasons: Melting of the Greenland ice sheet will add fresh water to the North Atlantic Ocean which have been theorized to weaken or even destruct the Atlantic MOC (Stouffer *et al.*, 2006). Secondly, the Greenland ice sheet stores a freshwater amount equivalent to an increase of the global sea level of 7 meters, implying that even partial melting will influence the global sea level in dramatic ways. Recent observation-based studies of the surface elevation of the Greenland ice sheet diverge; reporting that the interior of the Greenland ice sheet has increased during 1992-2003 (Johannessen *et al.*, 2005), that there is a net positive mass balance for the whole ice sheet for the same period (Zwally *et al.*, 2005), and that there has been a dramatic glacier acceleration between 1996-2005 (Rignot and Kanagaratnam, 2006). The fresh water discharges create the East Greenland Coastal Current (Wilkinson and Bacon, 2005), corresponding to at least 30 % of the total Arctic freshwater gain. Clearly, both the fresh water from the Greenland Ice Sheet and the freshwater transport out of the Arctic are of key importance for the Arctic and global climate system. Therefore, IPY-CARE will bridge historical and new observations and numerical modelling to study and quantify the fresh water from the Greenland ice sheet through the East and West Greenland Coastal Currents, the Arctic sea ice and the major Russian rivers.

A consensus from coupled atmosphere–ocean modelling studies of increasing greenhouse-gas (GHGs) scenarios is that anthropogenic global warming will be enhanced in the northern high latitudes (IPCC, 2001; Raisanen, 2002; CMIP2, 2003; ACIA, 2005) due to complex feedback mechanisms in the atmosphere–ocean–ice system. The predicted warming in the Arctic over the next 50 years is ~3-5°C, or more than twice the global average (IPCC, 2001; ACIA, 2005). This suggests that the Arctic may be where the most rapid and dramatic climate changes (e.g., a shrinking sea ice cover and reduced glacier and ice sheet volumes) may take place during the 21st century. However, both instrumental observations (like the early 20th-century warming) and modelling show that the Arctic is a region of large natural climate fluctuations (Sorteberg *et al.*, 2005; Bengtsson *et al.*, 2006). In depth analyses of the Arctic climate's signal-to-noise ratio is therefore a prerequisite for both proper quantification of the human-induced contribution to existing and future changes in the Arctic climate system, and to quantify the capabilities and reduce the uncertainty of climate predictions for the Arctic.

IPY-CARE will address the challenge of the Arctic climate signal-to-noise ratio in past, present and future by performing high-resolution sediment coring covering the last 10.000 years from lakes on Svalbard and of the Atlantic Inflow through the Fram Strait and in the Northern Barents Sea. IPY-CARE will extend the knowledge of past climate variability, present climate based on historical and new instrumental observations and tailored numerical modelling to quantify the signal-to-noise ratio and thus reduce the uncertainty for climate predictions.

The Arctic marine ecosystems (Stenseth *et al.*, 2002) and the cycling of carbon

(Skjelvan *et al.*, 2005) are subject to strong variability caused by effects of atmosphere-ocean-ecosystem fluctuations governed by e.g. NAO/AO (Hurrell *et al.*, 2003; Overland and Wang, 2005a), ice cover and irradiance. Climate models indicate that the Arctic Ocean may be without sea ice in summer in the second half of this century (Johannessen *et al.*, 2004) (Fig. 2). Such a situation, dubbed "Blue Arctic", will influence biodiversity, the marine ecosystem and the regional climate in dramatic ways, another wildcard of the climate. Presently, there is also a lack of understanding of the processes coupling the atmospheric boundary layer with sea ice, the water column and the marine ecosystems (Walsh *et al.*, 2005; Wassmann *et al.*, 2006). Moreover, a change in the climate system will affect the physical properties of the air-sea interface and biological production, both influencing the driving forces of the air–sea exchange of carbon dioxide (CO_2) (Anderson and Kaltin, 2001; Bellerby *et al.*, 2005). A shift in the ventilation of deep and intermediate waters will also change the transport and mixing of CO_2 from the surface to the deep waters, contributing to the sequestration of anthropogenic CO_2 – the extent to which is essentially unknown (Anderson *et al.*, 1998; Anderson and Kaltin, 2001; Olsen *et al.*, 2006).

IPY-CARE will address these issues by dedicated field experiments in the partial ice-covered Barents Sea and the Arctic Ocean. The field work will be complemented by high-resolution modelling of the marine biota and the cycling of CO_2.

A related issue of great concern is linked to the present and future acidification of the water column as a result of the ocean uptake of CO_2 (Bellerby *et al.*, 2005; Orr *et al.*, 2005) and consequences for ecosystem and biogeochemical transformations (Delille *et al.*, 2005; Engel *et al.*, 2005). IPY-CARE will address this challenge with controlled ecosystem mescosm experiments, studying Arctic species for possible future climate regimes, at the Marine Laboratory at Ny-Ålesund, Svalbard. These results will be upscaled with regional and large scale models describing the physical and biogeochemical states of the Blue Arctic.

From the state-of-art and the scientific rational, the objectives and research activities of IPY-CARE will advance the science of the Arctic climate system for the benefit of the society and future generations, as outlined below.

Questions and hypotheses

The contention of IPY-CARE is that the present paradigm of the NAO/AO coupled atmospheric–ocean–ice mode of variability as the predominant driver of Arctic climate variations through the range of time scales is not satisfactory. We hypothesize that other modes of variability – and their interactions and teleconnections to tropical and extra-tropical regions – are under-appreciated, especially when amplified through dynamical feedback processes into the Arctic ocean–ice–atmosphere system. The pronounced early 20th-century Arctic warming (Fig.1) has been theorized to be a natural internal mode of variability (Schneider *et al.*, 2003; Bengtsson *et al.*, 2004; Johannessen *et al.*, 2004), while the recent and ongoing warming has an anthropogenic signal, possibly superposed on – and interacting with – a natural low-frequency oscillation (Delworth and Mann, 2000; Koberle and Gerdes, 2003; Johannessen *et al.*, 2004). We hypothesize therefore that the early 20th-century warming is not an analog for the recent and future warming, which will be increasingly anthropogenic. Therefore, the 21st century Arctic represents a new "terra incognita" with an unprecedented state and unknown response; e.g., the summer ice cover may be less stable than presently believed (Serreze *et al.*, 2003; Johannessen *et al.*, 2004) (Fig. 2).

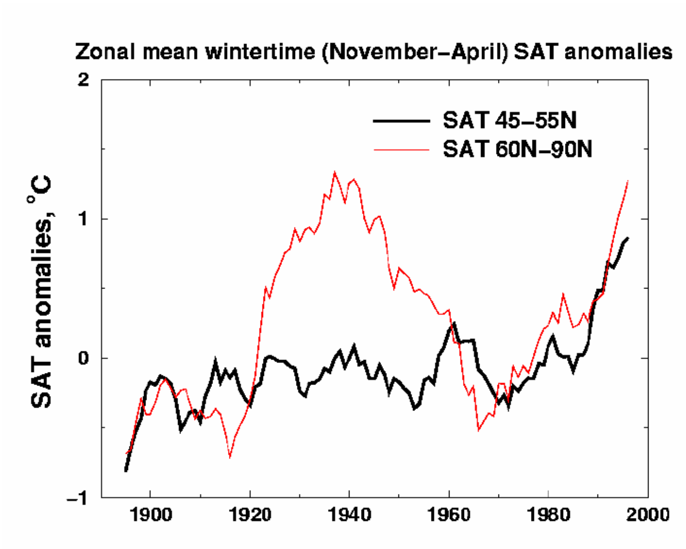


Figure 1. Winter surface air temperature (SAT) in the Arctic (60-90ºN) during the 20th century, compared to mid-latitudes (45-55ºN), indicating greatly amplified variability in the Arctic. From Bengtsson et al., (2004).

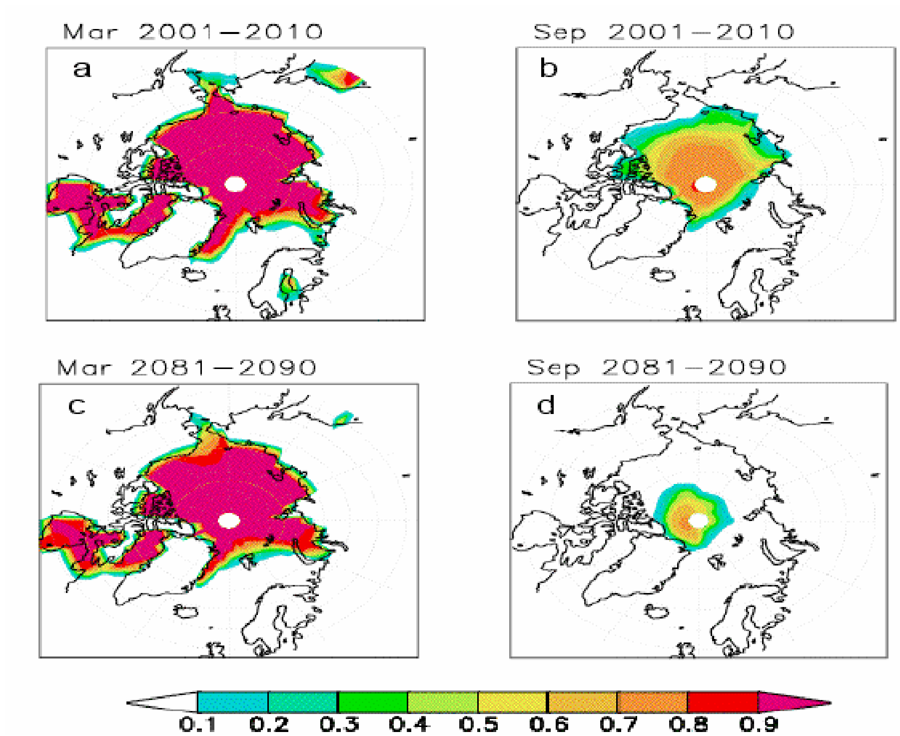


Figure 2. Arctic sea-ice extent in winter and summer during the 21st century, as modeled using the Max Planck Institute for Meteorology ECHAM-4 model. a) Winter, present decade, b) Summer, present decade, c) Winter, 2081-2090, d) Summer, 2081-2090. From Johannessen et al., (2004). The simulation uses IPCC92 IS92 emission scenarios.

The ocean transports large amounts of heat (~0.25 $\times 10^{15}$ W) to the Arctic via the THC, transforming surface and upper-layer incoming warm and salty buoyant waters of subtropical origin into deep outflowing cold and dense waters after gradual mixing with fresh and cold polar waters, to form the main body of the North Atlantic Deep Water (NADW). We hypothesize that most of this heat loss contributes to: (1) brine formation in polynyas on shelves, (2) deep convection and ventilation of the deep ocean, (3) cooling of Atlantic waters intruding the Nordic Seas and the Arctic Ocean, and (4) ocean heat fluxes through the Arctic cold halocline and sea ice. The key questions to be answered here include: What is the relative importance of each of these processes, how do they vary and interact, how sensitive are they to external influences (freshwater input, incoming radiation, anthropogenic impact, etc.) and what are the potential feedbacks affecting climate?

The freshwater input comes mainly from the Russian rivers, melting of sea ice and discharge from Greenland Ice Sheet and smaller glaciers in the Arctic. The Arctic glaciers have, in general, retreated over the same period (Dyurgerov and Meier, 2000; Rignot *et al.*, 2004), whereas less is known about the Greenland ice sheet (Johannessen *et al.*, 2005; Zwally *et al.*, 2005; Rignot and Kanagaratnam, 2006), one of the wildcards of the climate system. The latter has been the subject of increased attention for two important reasons: Melting of the Greenland ice sheet will add fresh water to the North Atlantic Ocean which have been theorized to weaken or even destruct the Atlantic MOC (Stouffer *et al.*, 2006). Secondly, the Greenland ice sheet stores a freshwater amount equivalent to an increase of the global sea level of 7 meters, implying that even partial melting will influence the global sea level in dramatic ways. One of the key questions is if the recent dramatic acceleration of the glaciers of the Greenland ice sheet is part of a natural variability or a major response of global warming. Furthermore, another question is how the increased freshwater discharge primarily caused by glacier acceleration will effect ocean circulation and deep water formation.

Analyses of paleoclimatological proxy data led to the conclusion that ice formation and brine release are the preferential mode for ventilating the deep ocean during glacial ages rather than deep convection driven by cooling during interglacial periods. Does the modern ocean have any preferential mode of ventilation or is it a mixed case?

Multidecadal to millennial variability of Arctic Ocean ice coverage and Atlantic Water inflow was a consistent feature in the ongoing interglacial period (ca. last 10 000 years) (Bianchi and McCave, 1999; Birks and Koc, 2002; Risebrobakken *et al.*, 2003). We hypothesize that in the 21st century feedback processes of anthropogenic and natural forcings will drive the Arctic climate system beyond the range of natural variability and may affect critical factors in the Arctic that determine the strength of the THC and the European climate.

A climate shift from a 'cold/abundant ice' to a 'warm/limited ice' mode will have profound ecological consequences propagating through all trophic levels, as sea-ice dynamics is the prime physical factor driving marine Arctic biology from cellular physiology and biochemistry to food web and habitat structure. We hypothesize that upon warming the relative importance of sea-ice biota, pelagic communities and benthic assemblages will shift from a 'benthos-dominated' to a 'zooplankton-dominated' mode (Fig. 3). This will fundamentally change the general pattern of cryo-pelago-benthic fluxes of matter and energy in Arctic seas, as well as the air-sea flux of CO_2.

The fact that the surface atmospheric temperature (SAT) has increased significantly (1.5-2°C) in the Arctic during the last 2-3 decades (Bengtsson *et al.*, 2004) (Fig. 1), that the ice cover has decreased with 3-4% per decade during the same decades (Johannessen *et al.*, 2004) and that models indicate that the ice cover will be dramatically reduced in this century (Johannessen *et al.*, 2004) (Fig. 2) requires that new assessment of the impact of these changes must be undertaken using the expected results from this proposed research.

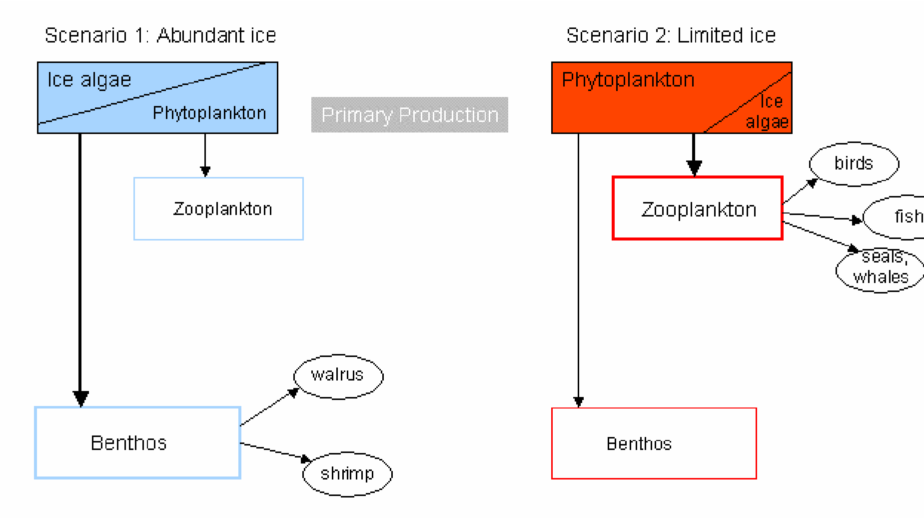
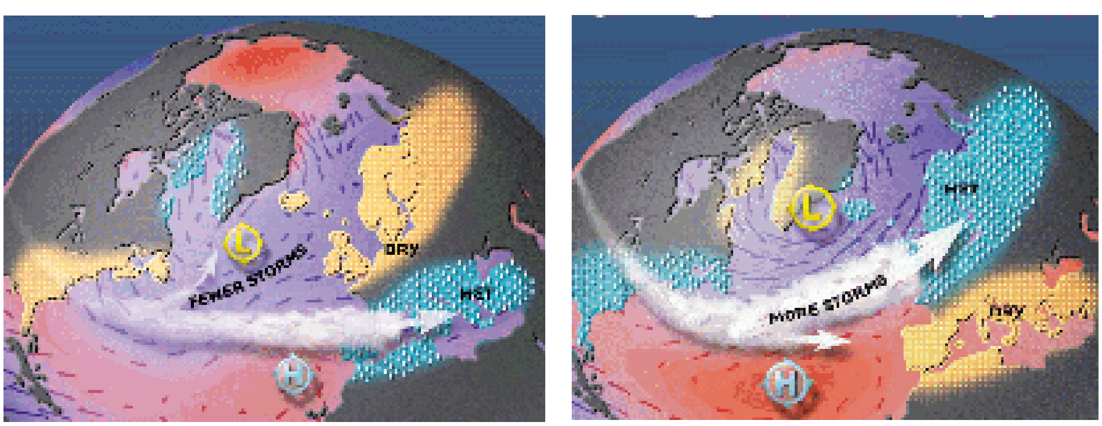


Figure 3. Conceptual model describing two climate-driven ecosystem modes differing in sea-ice cover, proportion of primary producers and, hence, general pattern of cryo-pelago-benthic coupling and trophic structure. From Carroll and Carroll (2003).

We hypothesize that the expected changes in the Arctic climate system will have far-reaching consequences for the freshwater budget and its effect on the THC (Rahmstorf, 1999; Fichefet *et al.*, 2003), significant impact on the ecosystem, fisheries and wildlife; impact on CO_2 uptake in the Arctic Ocean; impact on transportation, offshore industry and oil and gas production; impact on indigenous people: and impact on climate in Europe including the Mediterranean region. For example, Fig. 4 shows the impact of the NAO on the climate of Europe. Positive NAO index gives warm, wet and stormier weather in Northern Europe and Eurasian Arctic, and dry weather in the Mediterranean region, while a negative index gives wet weather in the Mediterranean region and dry, cold and less storms in the North (Kuzmina *et al.*, 2005).



a b

Figure 4. Schematic illustration of North Atlantic Oscillation (NAO) for (a) negative index and (b) positive index (http://www.ldeo.columbia.edu/NAO/).

Overall approach

To achieve the objectives of IPY-CARE major institutions involved in Arctic research in Europe, Russia, USA and China will be partners. The activities in IPY-CARE will include a number of joint activities such as: (1) Collection, analysis and harmonisation of historical and new modern data sets; (2) Development of new *in situ* observation systems; (3) Arctic field experiments; (4) Remote sensing observation systems from satellites, ice boys and underwater platforms; (5) Global climate models with improved parameterisation and validation; (6) Exchange programmes for scientists and training for students; (7) Co-ordinated dissemination and exploitation activities; (8) Technology development and scientific service transferred to SMEs; and (9) Modelling and prediction of the Arctic climate.

In addition to analysis of existing observational data, there will be significant acquisition of new oceanographic, sea ice, meteorological and ecological data from field experiments during the IPY, using ships, ice-going vessels, icebreakers and hovercraft from the partner institutions. Moreover, the project will use state-of-the-art and new ice-buoy and subsurface float technology for sea ice and ocean data acquisition. In addition to existing satellite observation methods, IPY-CARE will develop, validate, incorporate and utilise new ice-thickness measurements from ice buoys. Satellite data will also be innovatively used for other cryospheric parameters, such as the study of the Greenland ice sheet elevation change and glacier dynamics. New sediment core data and reconstruction techniques for high-resolution studies of past climates and paleooceanography will be developed and used in conjunction with models. New data and techniques for modelling the response of marine ecosystems to climate change will be developed and applied. Stateof-art global coupled atmosphere–ocean models and models for climate processes and air–sea–ice meso-scale processes will be improved and used to study climate variability.

The work will be implemented in six (6) integrated scientific workpackages:

WP1: Processes determining Arctic climate variability and changes;

WP2: Marine biological processes in response to climate change;

WP3: Air–sea–ice meso-scale processes and climate variability;

WP4: Past climate variability;

WP5: Remote sensing and new technology for climate data provision, and

WP6: Assessment of Arctic climate change impact

The workpackages are closely linked, as illustrated in Fig 5, and successful research in one of them depends to a large extent on results from the others.

WP1 deals with observational data as well as modeling and will deliver observational and modelling datasets to WP2, data on ocean circulation and freshwater patterns to WP3, and millenniumscale modelling data to WP4. Furthermore, it will quantify the linkages between the Arctic and lower latitudes and scenarios of future climate change for input to WP6. WP2 will deliver an ecosystem model and parameterisation to WP1 and a convection model to WP3. WP2 will provide estimates of the effects of climate change on ecosystems and the CO_2 cycle to WP6. WP3 will provide process-oriented datasets and parameterisation to WP1, physical mesoscale data from field experiments and convection models to WP2, information on present THC variability to WP4, data for remote sensing validation to WP5, and information on freshwater, convection, radionuclides transport and the THC to WP6. WP4 will provide new paleo datasets and variability estimates to WP1, past THC variability to WP3 and estimates of past natural *vis à vis* anthropogenic variability to WP6. WP5 will provide data sets from reconstruction in WP4. WP5 will also provide operational met-ocean-sea ice data for transportation and offshore activities assessed in WP6. The WP6 assessment activities depend on the scientific basis input from WPs 1-5, as specified above.

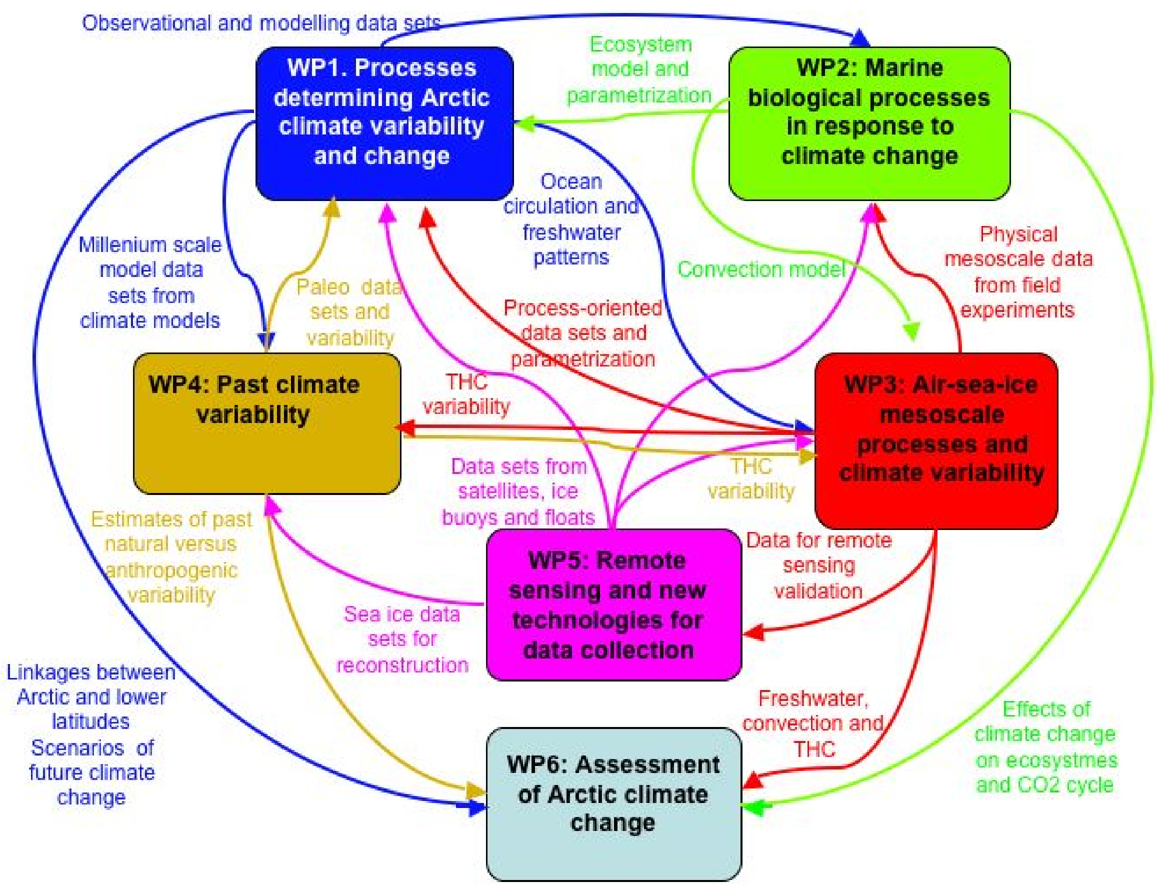


Figure 5. Links between the WPs in IPY-CARE

There will be substantial "horizontal" activities throughout the IPY-CARE work programme extending across the workpackages and tasks. These horizontal activities are dedicated to: (1) Coupling between research and education, particularly to enhance training of doctoral and post-doctoral scientists, and (2) Dissemination and exploitation of the scientific, technological and practical results that will be produced, including technology development and scientific service transferred to SMEs.

WP1: Processes determining Arctic climate variability and changes

WP-leader: L. Bengtsson (MPI); Co-leaders: U. Schauer (AWI) and I. Frolov (AARI)

Objectives

The first main objective of WP1 is to identify and analyse key mechanisms that determine the interannual to decadal scale climate variability modes in the Arctic. Such knowledge is of key importance for understanding the role of the Arctic in the global climate system, and it is a prerequisite for reliable climate predictions for the region. The second main objective is to assess to which extent and in which way human-induced global warming will influence the mean and regional evolution of the Arctic climate system in the 21st century.

Background

Over the last century the surface temperature of the Arctic has undergone significant changes with a warm period in the 1930s and 1940s, a cold period in the 1960 and 1970s, and a marked increase in the surface temperature since the 1980s. Available instrumental and proxy observations show that the Arctic climate tends to undergo large variations on decadal to multi-decadal time scales. The most prominent example is the early 20th century warming with surface temperatures poleweard of 60ºN that are comparable to the present day temperature (Delworth and Mann, 2000; Bengtsson *et al.*, 2004). A fundamental question is whether these climate fluctuations are enforced through teleconnections, for example tropical convective forcing initiated by e.g. sea surface temperature anomalies, by changes in the poleward oceanic transport of heat and/or the atmospheric transport of heat and moisture, or by internal fluctuations of the Arctic climate system. Furthermore, simulations of the future climate show that the largest warming will occur at the high northern latitudes (Cubasch *et al.*, 2001; Räisainen, 2001). While the early 20th century warming in all likelihood was a natural mode of the climate system (Delworth and Knutson, 2000; Bengtsson *et al.*, 2004; Johannessen *et al.*, 2004), the present warming is likely influenced by the ongoing anthropogenic climate forcing. An important objective of the work package will be to exploit past and present observation-based evidence and to perform tailored modelling to thoroughly assess whether this is the case.

Climate changes in the Arctic is expected to influence the global climate and particularly so in the European area. This could take place through a weakened North Atlantic thermohaline circulation in response to increased melting of the Greenland ice cap, Arctic glaciers and the Arctic sea ice. Reduced salinity in the North Atlantic is also expected to follow from increased precipitation and possibly also reduced evaporation in the North Atlantic due to less cold arctic air masses during the winter. A spin-up of the hydrological cycle is indeed simulated by most climate models forced with increasing levels of atmospheric greenhouse gases (Cubasch *et al.*, 2001; Räisainen, 2001).

At the high northern latitudes, a combination of warming and dilution of the surface ocean will tend to inhibit formation of intermediate and deep water masses both in the North Atlantic Subpolar Gyre (SPG), within the Nordic Seas and in the Arctic Ocean, and possibly result in a weaker North Atlantic

Thermohaline Circulation and a less efficient oceanic heat conveyor (Cubasch *et al.*, 2001; Quadfasel, 2005). Questions of outmost importance are: What is the relative probability of a colder versus warmer future Arctic climate on time scales from decades to a century (Sorteberg *et al.*, 2005)? Which mechanisms can lead to a colder Arctic, and on which time scales? Are the time scales and signatures of Arctic natural variability of such a nature that reliable decadal predictions can be made?

Gradual melting of the Arctic sea ice, and the possibility of an essentially ice-free Arctic Ocean in summer ("Blue Arctic") poses a series of questions related to the climate response through changes in the surface albedo and in the air-sea exchange of momentum, heat, fresh water and carbon dioxide, consequences for the marine life from plankton species to fishes, seals, polar bears and birds, and implications for local human communities and for infrastructure like shipping and exploitation of oil, gas and known and unknown mineral recourses.

In the following, short descriptions are given for the main physical components of the Arctic climate system.

Atmospheric processes

A global warming related to increased greenhouse gas concentration in the atmosphere is expected to lead to a number of changes that may effect the general circulation of the atmosphere. Model experiments suggest a decreased meridional gradient in the lower troposphere and an increased gradient in the upper troposphere. At the same time the tropopause is rising. The effect of this implies a more stable stratification at low latitudes and less stable vertical stratification at higher latitudes. The amount of water vapour will increase, broadly following the Clausius-Clapeyron relation as models and observations appear to conserve the relative humidity. The increased amount of water vapour in the atmosphere would mean more efficient transport of heat to higher latitudes thus requiring less intense vortices as the needed transport can be handled will less energetic eddies. As greenhouse gases cools the high latitude stratosphere circulation will intensify and this will be further enhanced by ozone depletion. A positive feedback may occur here as the catalytic actions of chlorine compounds are activated at lower temperatures.

Changes in the overall storm track

Storm tracks in the Pacific are strongly influenced by ENSO and the warm events enhance the advection of warm maritime air into the Arctic in the Alaskan sector. The storm tracks in the Atlantic sector have no obvious boundary forcing but appear to be dominated by chaotic processes. The support for this is the inability of models to reproduce the storm tracks in similar experiments even if boundary conditions such as sea surface temperatures are unchanged.

The storm tracks in the eastern North Atlantic have two general preferred tracks, one over Island and north-eastward towards Spitsbergen and another on a typical easterly track south of the Scandinavian Peninsula. These storm tracks are symbiosis related to the North Atlantic Oscillation (NAO) (Loptien and Ruprecht, 2005). While it has been suggested that NAO may be critical for the climate of the Arctic (Hurrell *et al.*, 2003) it appears that even more important could be a storm track in a very northerly position not directly related to the NAO (Bengtsson *et al.*, 2004).

Several recent studies have indicated a pole ward transition of the storm tracks (Kushner *et al.*, 2001; Geng and Sugi, 2003; Sorteberg *et al.*, 2005; Bengtsson *et al.*, 2006). This pole ward transition is most clearly seen in the Southern Hemisphere during summer but similar changes can also be seen in the Northern Hemisphere with reduced wintertime transient cyclone activity in the Mediterranean region and enhanced cyclone activity over the eastern North Atlantic. There are no significant storm track changes in the Arctic except a minor increase during summer.

Changes in the stratospheric circulation

Both empirical and modelling studies suggest that the circulation of the Antarctic vortex has intensified due to an overall stratospheric cooling over the Antarctic continent. This has even intensified the westerlies through the troposphere leading to enhanced advection of maritime area and associated warming over the Antarctic Peninsula, although cooling has occurred in most other Antarctic regions. The main cause of the stratospheric cooling seems to be related to ozone depletion. There is no clear indication of a similar development at the Northern Hemisphere although extreme temperatures in the Arctic stratosphere have gradually become colder during late winters. It has been suggested that the dominant westerly circulation in the last three decades over the North Atlantic (positive phase of the NAO) bringing warmer and wetter weather to western and northern Europe could be related to a more active Arctic stratospheric circulation similar to that of the Southern Hemisphere. However, it is equally likely that the troposphere is driving the stratosphere and the cause could be related to storm track changes.

Oceanic processes

The ocean component is of key importance for the climate of the Arctic region. Since the temperature of open water never drops below -2 °C, particularly strong air-sea fluxes of heat, fresh water and carbon dioxide are found in the Arctic region in all but the few summer months. It is therefore needed to consider the Arctic region as a truly coupled climate system with strong interactions between the atmosphere and the ocean.

The Arctic Ocean is strongly stratified, with a thin layer of fresh water at the surface, and with a relatively saline layer below. The Arctic upper layer is fed by fresh water drainage from the vast continents surrounding the Arctic Ocean. The upper waters of the Arctic Ocean are characterized by a shallow mixed layer at or near freezing temperature, overlying a pronounced cold halocline (Rudels *et al.*, 1996). The halocline leads to a very stable vertical density structure in the central Arctic. This vertical stability is important as it isolates the surface waters, and by that the Arctic sea ice, from the heat carried with the relatively warm Atlantic water found at depths of 500-700 m. A reduced halocline will tend to increase the upward flux of Atlantic water, and by that melting of the Arctic sea ice. It is therefore critical to identify and to assess the relative importance of the processes that determine the vertical density stratification in the Arctic Ocean for the present day climate and for a climate resulting from increasing concentrations of greenhouse gasses and particles.

Further south, the freshwater content (FWC) in the North Atlantic SPG has shown large changes during the last decades (Curry and Mauritzen, 2005). The most striking event occurred in the early 1970s, labeled the Great Salinity Anomaly. This anomaly has been attributed to a large pulse of freshwater (Dickson *et al.*,

1988) and sea ice (Haak *et al.*, 2003) originating from the Arctic Ocean. Likewise, Hatun *et al.* (2005) demonstrated that the structure and intensity of the North Atlantic SPG are controlling factors for the input of high-salinity waters to the Nordic Seas and likely to the Arctic Ocean by the inflows through the Barents Sea and the Fram Strait. The state of the Arctic Ocean is therefore tightly coupled to the dynamics of the North Atlantic and vice versa, showing that a holistic view is needed to properly address the ocean component of the Arctic region.

Sea ice and snow cover

Arctic sea ice undergoes natural changes on different time scales. Recent observations suggest that sea ice extent is record low and model calculations based on mid and upper IPCC scenarios suggest that the sea ice will disappear in summer towards the end of this century (Johannessen *et al.*, 2004). It appears that the main forcing is the atmospheric and ocean circulation that bring warm air and warm water into the Arctic via the Norwegian Sea. Due to the strong feedbacks associated with sea ice melting and enhanced absorption of solar energy in the upper ocean during the summer months, the reduction in sea ice will further strengthen the Arctic warming. Furthermore, the melting of the sea ice will also effect the ocean circulation and the deep water formation.

Melting of the Greenland ice sheet

The Greenland ice sheet is one of the wildcards of the climate system. Recent observation-based studies of the surface elevation of the Greenland ice sheet diverge; reporting that the interior of the Greenland ice sheet has increased during 1992-2003 (Johannessen *et al.*, 2005), that there is a net positive mass balance for the whole ice sheet for the same period (Zwally *et al.*, 2005), and that there has been a dramatic glacier acceleration between 1996-2005 (Rignot and Kanagaratnam, 2006). The fresh water discharges create the East Greenland Coastal Current (Wilkinson and Bacon, 2005), corresponding to at least 30 % of the total Arctic freshwater gain. Clearly, both the fresh water from the Greenland Ice Sheet and the freshwater transport out of the Arctic are of key importance for the Arctic and global climate system.

River runoff

An essential part of the ocean dynamics of the Arctic is the fresh water balance (Bobylov et al., 2003). The river runoff into the Arctic Ocean has increased by about 7 % between 1936 and 1999 (Peterson *et al.*, 2002). In the last two - three decades the increase has been more significant, as shown by Shiklomanov *et al.*, (2000). This result is on based on synthesis of river monitoring data of six largest Eurasian rivers to the Arctic Ocean. The ACIA climate model predictions suggest that precipitation and river runoff will continue to increase in this century (ACIA, 2005). It is therefore important to maintain monitoring of the fresh water supply of the major rivers entering the Arctic Ocean.

Past Arctic climate

Paleoclimatic studies can contribute to the understanding of climate processes by examining past periods that were radically different from the present climate. Accumulating data point to a comparatively warm early Holocene in the Arctic– warmer than today, and the early medieval warm period is in some instances regarded as a period of similar warmth as today. The detection of anthropogenic climate change in observations and the validation of climate models and climate change feedback rely on improved understanding of natural climate variability. There are many initiatives proposing to assemble very high-resolution data sets on paleoclimate for the last 2000 years. Some of this data is already in hand, but some will be obtained within the next couple of years. This kind of data will without doubt contribute to the efforts in differentiating between natural and anthropogenic climate variability.

Integrated use of observations and models

Use of best available data sets and models

To properly address these issues we propose a series of major model experiments and associated data studies with state-of-the-art coupled models and best available data sets. Particularly important will be to resolve the characteristic orography and bathymetry of the region and the sharp and intense ocean currents. We suggest employing global coupled models with extra high resolution in the Arctic as well as using embedded limited area atmospheric or ocean models of very high resolution.

Central questions:

1. It has been suggested in several studies (Hurrell, 1995; Hurrell *et al.*, 2003) and it was also the primary hypothesis in the SEARCH programme, that the North Atlantic Oscillation (NAO) or Arctic Oscillation (AO) is instrumental in influencing the Arctic climate. However, in recent five years we have seen a rapid Arctic warming and record low Arctic sea ice extent while at the same time NAO has been virtually zero (Overland and Wang, 2005b), and it has been speculated if this implies that the albedo feedback is now so strong that the Arctic sea ice is continuously melting regardless of the atmospheric circulation pattern (Lindsay and Zhang, 2005). Key questions are: *What are the key atmospheric and oceanic conditions, which dominate the Arctic climate and how do they interact?*

2. The direct causes of the rapid decrease of Arctic sea ice are not well understood. *What are the contributions from atmospheric and oceanic heat transports respectively, what is the contribution from radiation changes (solar and terrestrial), and what is the role of the internal feedback mechanisms (e.g. albedo and cloud feedbacks)?*

3. The huge temperature changes in the Arctic; warming in the 1930 and 40s and the cooling in the 1960 and 70s are likely caused by natural processes: *What are these processes? Are they due to internal low frequency processes or just the integrated effects of stochastic synoptic events causing a reddening (low frequency shift) of the energy spectrum (Hasselmann, 1976)? And if external forcing, what are then credible atmospheric and/or oceanic mechanisms?*

4. For the next few decades the anthropogenic forcing of the climate system can be assumed to be reasonably well known as major changes in global energy usage are not feasible on this time scale. If so an urgent issue will be to estimate the robustness of the present sea ice condition in the Arctic with respect to the present climate condition: *What is the probability for a recovery to a situation prior to the late 1970s? What is the probability for a further rapid reduction of sea ice? And what is the range of possible Arctic climate states in general for the next few decades?*

5. The strong freshening of the Nordic Seas and subpolar gyre from the 1960s to the 1990s (Curry *et al.*, 2003; Dickson *et al.*, 2003; Curry and Mauritzen, 2005) has reduced the north-south density gradient in the Atlantic Ocean, and Bryden

et al. (2005) reports of a 30% reduction in the deepest southward flow in the North Atlantic, which are believed to originate from the Nordic Seas. In contrast, no long-term changes are seen in 10 year long direct observations of Atlantic inflow to the Nordic Seas or overflow to the North Atlantic. Several questions need to be addressed: *What is the present state of the thermohaline circulation? What is the effect of increased precipitation, river runoff and sea ice and glacial melting in the high north? What is the likelihood of a cooling of Europe?*

6. The Greenland Ice Sheet is a wildcard in the climate system, where melting and glacial acceleration causes freshwater input to the ocean and increased sea level. It has been shown that NAO is negatively correlated to the surface elevation in the interior of the ice sheet, causing accumulation in the last decade while accelerated glacial melting in the last few years has caused dramatic increase of freshwater discharge: *Which are the dominant factors that control the changes in the mass balance of the Greenland ice sheet?*

7. When using paleodata, it is particularly important that the models employed have similar spatial scales as the data. It is well known that global climate models exhibit most skill at larger spatial scales. This is a significant limitation to the evaluation of paleoclimatic experiments, since most proxy data represents a significantly smaller footprint. To address this problem, *regional climate models or global models with increased resolution in key regions should be used for dynamical downscaling. Another alternative is statistical downscaling (Reichert et al., 2002), or a combination thereof.*

Research Strategy:

A strategy towards addressing the Arctic climate issues will include advanced modelling combined with detailed systematic validation with available observations including century long meteorological and oceanographical time series, as well as more hemispheric wide synoptic reanalysis or remote sensing data. Three main actions are identified:

i) To put together a comprehensive climatology for at least the last 100 years. This will include basic climate parameters for atmosphere, land and ocean with estimated error bars. Priorities on surface temperature, pressure, precipitation, snow cover, sea-ice, ocean temperature and river run off. Sampling is needed on at least monthly resolution and wherever possible on daily resolution. If feasible an Arctic climate reanalysis effort should be considered (Bengtsson, 2006).

ii) To set up a systematic numerical experimentation programme using a series of selected global climate models including the ECHAM/OM1 and the Bergen Climate Model combined with selected limited area climate models. These models should be run at highest possible resolution from 1900 (100+ year hindcast) until 2030 in an ensemble mode. Major science effort will be devoted to assess these experiments in order to identify what are natural processes and anthropogenic influences and generally to determine the predictability of the climate system.

iii) To undertake a variety of process studies aimed at improving the performance of the Arctic climate models. This should cover a broad suite of activities and will be set up so that new observations from IPY could be tested and evaluated.

Process modelling

The following examples describe a range of important processes that need improved modelled:

a. *Sea-ice freezing, melting and deformation processes*. Here priority should be on a best possible representation of sea ice for an accurate energy exchange with the atmosphere and for the dynamics of first and multi-year sea ice, and changes to the fresh water and salt budgets.
b. *Land surface processes*. Here the treatment of snow preferably in combination with vegetation needs to be improved. Furthermore, permafrost and vegetation changes due to permafrost melting must be properly handled in the models.
c. *Hydrological cycle, river run off and glacier melting*. Glacier melting in particular is an area that needs significant improvements.
d. *Atmospheric heat and moisture transport*. Understanding the variability and changes related to the amount of heat and moisture transport into the Arctic should be pursued. This would require global and preferable high-resolution AGCMs or coupled climate GCMs.
e. *Heat and salinity transport in and out of the Arctic*. Here high-resolution and extensively evaluated Ocean General Circulation Models are required.
f. *Atmospheric boundary layer*. Detailed simulation of the turbulent processes are needed to disclose the fundamental processes involved for the major type of boundary layers, and how the atmospheric boundary layer can be incorporated into global-scale coupled climate models.
g. *Cloud representation and its role in Arctic energy balance*. The mix of different types of cloud particles in liquid and frozen phase, and the importance of Dimethyl Sulfide (DMS) as a source of cloud condensation nuclei (CCN) need to be assessed and appropriately incorporated in global-scale coupled climate models.
h. *Stratosphere-troposphere interaction*. It is still an open question whether stratosphere-troposphere interactions are responsible for large-scale and persistent circulation anomalies in the Arctic, or vice versa. Also the role of the Arctic ozone needs to be assessed.
i. *Chemical processes in the Arctic atmosphere* and its effect on cloud and precipitation

A hierarchy of model experiments

Experiment 1. Conduct an ultra-long simulation encompassing some 1000 years with no variation in the external forcing. The purpose of this integration is to examine the internal modes of the climate system that affects the Arctic climate. This will include detailed evaluation of characteristic variations in ocean and atmospheric circulation, water and energy cycles of the Arctic including net transport of sea-ice circulation. Also the relation between Arctic anomalies and climate anomalies elsewhere, e.g. NAO and SO will be studied. We expect that this will demonstrate the capability of coupled models of the early 21st century and much better clarify the range of natural variability of the Arctic climate system. It will also provide useful data for the intercomparison with paleo data and thus close interaction with WP 4. To better understand the climate of the last 100 years a series of shorter integrations with observed changes in the forcing will be undertaken. An important result of this experiment would be to better clarify the cause of the major climate variations of the 20th century.

Experiment 2. Using best available boundary conditions from sea ice, snow cover, SST etc. and observed forcing (GHG, anthropogenic aerosols, volcanic aerosols etc.) to carry through an ensemble simulation (minimum five members) of the climate of the 20th century. Here stand-alone atmospheric models are sufficient. The main purpose of this type of experiment would be to explore the extent to which the Arctic climate can be "reproduced" by imposing the external forcing and appropriate ocean and land surface boundary conditions. This will help setting an upper limit of predictive skill (assuming in principle a perfect prediction of ocean and sea-ice) and thus have important consequences for estimating climate predictability (Collins *et al.*, 2006).

Experiment 3. Using best available atmospheric data, such as from the new ERA-40 reanalyses and the latest re-analyses from NCEP/NCAR to force an ocean/sea-ice model. The purpose of this task, which will be undertaken in close co-operation with WP3, will serve to validate the ocean/sea ice models and explore to what extent state-of-the-art ocean/sea ice models can reproduce characteristic and crucial features of the Arctic Ocean circulation. This will include, as observed, variations in sea ice, ocean currents at different depths and variations in ocean temperature and salinity including the great salinity anomaly of the 1960s and 1970s, and the record-warm and saline inflow of Atlantic waters since 1995. While the main emphasis will be on the period 1950 to present, because of the availability of re-analysis data, efforts will be made to assess atmospheric forcing fields for periods prior to 1950 based on available surface observations.

Experiment 4. There have been several attempts to simulate the response of the climate to increased fresh water discharge to the North Atlantic or Arctic (Otterå *et al.*, 2003; Otterå and Drange, 2004; Otterå *et al.*, 2004). Most simulations have either been carried out with a very coarse climate model that is not capable of adequately resolving the ocean circulation, or with unrealistic discharges either by using discharge rates several orders of magnitudes higher than what is realistic, or by distributing fresh water evenly over a large area instead of releasing it at the coasts which is most realistically. It is therefore a need to use state-of-the-art climate models with realistic fresh water amounts and sources.

Experiment 5. Very high-resolution experiments with advanced coupled models used in a forecasting mode to support the CARE field experiments. This will include close co-operation with WP 3. The length of these field experiments is expected to be less than a year.

Experiment 6. Predictability experiments with coupled models under i) in an ensemble mode as for the atmosphere-alone integrations in ii) but forced with selected IPCC scenarios. Such experiments can be limited to a maximum of 50 years and focus the effort on decadal predictability (Sorteberg *et al.*, 2005; Collins *et al.*, 2006) and the identification of possible extreme events. Important questions include: Will the members of the ensemble differ from a typical random distribution in any particular way. What are the changes in the statistics of climate including extreme events? This experiment will answer the question whether it will be feasible to provide any assessment of the overall time evolution of climate change for the next 50 years or so. Can we for example deliver upper and lower bounds of say decadal averages of temperature and sea-ice distribution which are better than what we now can get from standard climate statistics?

Experiment 7. Climate change experiments are needed to determine a best estimate and the associated uncertainty of climate projections for the Arctic region on time scales from decades to a century. It is here needed to use model systems that are capable of simulating the present day climate system in a way that resembles the observed climate state. Special emphasis should be given to the treatment of air-ice-sea interactions and clouds as these processes are of crucial role for the Arctic climate. Also the marine cycling of carbon should be assessed since it is still an open question whether a Blue Arctic will act as a net source or sink of atmospheric CO_2. Reliable simulations of the Arctic climate system require a model resolution that is generally well beyond what the current state of climate GCMs use. Therefore local grid refinement in the Arctic region is highly recommended.

Research Plan

WP1.1 Historical and modern observational data

Partners: Schauer (AWI), Johannessen (NERSC), Hagen (UiO), Furevik (UoB/BCCR), Drinkwater (IMR), Gascard (UPMC/LODYC), Alekseev (SRC AARI), Bobylev (NIERSC), Jevrejeva (ESARC), Bojariu (INMH), Morison (APL/UW), Overland (PML/NOAA)

Task: To extend the existing database for the Arctic and sub-Arctic region
Methodology / work description:
The data will be used for analyses of climate processes, model validation and to support the initialisation of model integrations when appropriate. Provision of data for the extended integration will be undertaken in close cooperation with WP4. To support the modelling of the Arctic climate of the 20th century work will be done to extend the existing database with specific emphasis on the Arctic and sub- Arctic region particularly for the first half of the 20th century. This will include supplementing existing data sets, production of up-to-date time series of different climate parameters including: surface and upper-air atmospheric data, SST and salinity; and sea-ice cover; land-surface data (precipitation, snow cover, river runoff to the Arctic Ocean). New ocean data will be obtained to specify the present state of the Arctic Ocean circulation, by carrying out focused field studies in the high Arctic, the Barents Sea, the Norwegian/Greenland Sea and along the coast of Greenland in cooperation with WP3-WP5. Special emphasis will be on the distribution and pathways of freshwater to the convection sites in the Arctic and sub-Arctic. To distinguish the contribution from different freshwater sources (ice sheet/glacier melt, sea-ice melt, river and continental runoff), tracers ($\delta^{18}O$) will be used in addition to T and S measurements.

WP1.2 Extended coupled model simulations to understand natural climate variability

Partners: Goosse (UCL-ASTR), Dethloff (AWI), Schmith (DMI), Bengtsson (MPIfMet), Drange (NERSC/BCCR), Furevik (UoB/BCCR), Karcher (OASYS), Kuzmina (NIERSC), Meleshko (MGO), Bojariu (INMH), Shukla (COLA), Wang (IAP)

Task: Long-term simulations of the Arctic climate to improve our understanding of the natural variability of the Arctic climate system including the THC and the energy and water cycles
Methodology / work description:
We will undertake ultra-long coupled model simulations encompassing some 1000

years with no variation in the external forcing. The purpose of these integrations is to examine the internal modes of the climate system, which affects the Arctic climate. This will include detailed evaluation of characteristic variations in ocean and atmospheric circulation, water and energy cycles of the Arctic including net transport of sea-ice. Linkages between AO and climate anomalies elsewhere, e.g., NAO and ENSO, will be studied. We expect that this will demonstrate the capability of coupled models of the early 21st century, including also nested limited area models, and better clarify the range of natural variability of the Arctic climate system. It will also provide useful data for the intercomparison with paleo observations to be undertaken in close cooperation with WP 4.

WP1.3 Processes governing the Arctic climate of the 20th century

Partners: Bengtsson (MPIfMet), Dethloff (AWI), Bamber (Unibris), Drange (NERSC/BCCR), Döscher (SMHI), Hagen (UiO), Partington (Vexcel UK), Kuzmina (NIERSC), Meleshko (MGO), Shukla (COLA), Wang (IAP)

Task: Forcing climate models with observed data for atmospheric composition and surface boundary conditions to provide insight in Arctic climate predictability

Methodology / work description:

Using best available boundary conditions of sea ice, SST etc. and observed forcing (GHG, anthropogenic aerosols, volcanic aerosols, etc.) to carry through an ensemble simulation of the climate of the 20th century. It is anticipated that a minimum of five experiments will be undertaken. Here, atmosphere-only models would be sufficient. The main purpose of this experiment would be to explore how well the Arctic climate can be "reproduced" knowing the forcing and the ocean boundary conditions. The models will have an appropriate representation of tropospheric and stratospheric processes. This will help setting an upper limit of predictive skill (assuming in principle a perfect prediction of ocean and sea-ice) and thus have important consequences for estimating climate predictability. To further the understanding of the climate of the last 100 years a series of integrations with observed changes in the forcing will also be undertaken but using coupled ocean–atmosphere models. An important result of these experiments would be to better clarify the impact of ocean– atmosphere interactions on the climate variations of the 20th century.

WP1.4 Processes determining the variability of the Arctic Ocean

Partners: Schmith (DMI), Gerdes/Lemke (AWI), Mikalojewicz (MPIfMet), Drange (NERSC/BCCR), Döscher (SMHI), Goosse (UCL-ASTR), Houssais (UPMC/LODYC), Karcher (OASYS), Alekseev (SRC AARI), Kuzmina (NIERSC), Wang (IAP), Haapala (FIMR)

Task: Forcing of Arctic Ocean and sea ice models and regional atmospheric climate models from atmospheric data, to validate the performance of the models against observations and to investigate processes relevant for the variability of the THC.

Methodology / work description:

Using best available atmospheric data, such as from the new ERA-40 reanalyses and the latest reanalyses from NCEP/NCAR to force ocean–sea-ice models. The purpose of this task, which will be undertaken in close co-operation with WP3, will serve to validate the ocean–sea ice models and explore to what extent state-of-the-art ocean–sea ice models can reproduce characteristic and crucial features of the Arctic Ocean circulation and the variation in sea ice. This will include, as observed, variations in sea ice, ocean currents at different depth and variations in ocean temperature and salinity including the great salinity anomaly of the 1960s and 1970s. While the main emphasis will be on the period 1950-2000+, because of the availability of re-analysis data, efforts will be made to assess atmospheric forcing for periods prior to 1950 based on available surface observations. Extended runs will be used to identify possible changes in oceanic and sea ice variability patterns that could be indicative of deviations from natural modes of variability. High-resolution regional atmospheric climate models will be used to provide an improved representation of the surface fluxes, especially for precipitation, evaporation and the meltwater runoff from the Greenland ice sheet, which together with sea ice melt/freezing are believed to play a crucial role for the variability of the THC in the North Atlantic. Very high-resolution experiments will be undertaken to support the CARE field experiments.

WP1.5 Carbon-cycle modelling: Present and future air-sea exchange of CO_2 in the Arctic

Partners: Drange (NERSC/BCCR), Maier-Reimer (MPIfMet)

Task: Undertaking hind-cast and prediction experiments of the marine cycling of carbon in the Arctic region with coupled, state-of-art physical-biogeochemical models

Methodology / work description:

A selection of the model integration activities described under 1.4 and 1.6 will be extended to coupled, regional scale physical-biogeochemical models to simulate the natural variability and possible large-scale changes in the cycling of carbon in the Arctic region over the last 50 years and in a warmer climate. The regional scale physical-biogeochemical models will have a horizontal resolution of about 20 km, and will be one-way coupled to the model output from selected integrations in 1.4 and 1.6. For the hind-cast simulation, observed nutrient and carbon-system parameters will be used to evaluate the simulated variability. The analyses will be focused on how and to which degree the inter-annual to decadal variations in the marine climate system influences the northern high-latitude marine cycling of carbon, and by that the air-sea exchange of CO_2. The analyses will be performed in close collaboration with WP2. Model realisations of the climate of the 21st century will be based on two of the selected IPCC scenarios in 1.6. Emphasis will be put on the combined effects retreated summer sea ice cover in the Arctic and increased precipitation and continental run-off to the Arctic have on the marine cycling of nutrients, carbon and the marine ecosystem (WP2), and by that on the air-sea exchange of CO_2.

WP1.6 Predicting the future of the Arctic climate

Partners: Drange (NERSC/BCCR), Bengtsson (MPIfMet), Furevik (UoB/BCCR), Döscher (SMHI), Hagen (UiO), Bojariu (INMH), Wang (IAP)

Task: Undertaking prediction experiments of the Arctic climate with state-of-art-coupled models

Methodology / work description:

Predictability experiment with coupled models under an ensemble mode as in WP 1.3, but forced with selected IPCC scenarios. We plan to extend these experiments to a maximum of 50 years and focus the effort on decadal predictability and the identification of possible extreme events. Important questions to be answered include: Will the members of the ensemble differ from a typical random distribution in any particular way. What are the changes in the statistics of climate including extreme events? This experiment will answer the question whether it will be feasible to provide any assessment of the overall time evolution of climate change for the next 50 years or so. Can we for example deliver upper and lower bounds of, e.g., decadal averages of temperature and sea-ice distribution that are better than what we now can get from standard climate statistics?

WP2: Marine biological processes in response to climate change

WP-leader: S. Falk-Petersen (NPI), co-leaders: D. Piepenburg (IPOE/ASM) and L. Anderson (UGOT)

Objectives

The overall objective is to study the interactions between present climate variability and primary and secondary production, biomass, community structure in sympagic, pelagic and benthic biota, and fluxes of gases and particulate matter. To address this objective, we propose collection of new marine biological, biogeochemical and physical data from sea ice, water column and seafloor and the boundary layers (air-sea, air-ice, ice-sea, and sea-sediment), analysis of historical data sets, lab experiments, and modelling work.

State of the Art

A substantial reduction and/or seasonal disappearance of sea ice in the marginal seas of the European Arctic will fundamentally change the structure and functioning of the Arctic marine ecosystem. A substantially ice-free Arctic margin will have water mass properties (horizontal and vertical), primary production/food source dynamics, biogeochemical transformations, and bio-physical linkages that are substantially different than at present. These in turn will lead to alterations of community structure and trophic dynamics.

The Marginal Ice Zones (MIZ) in Arctic seas are some of the most dynamic areas in the world's oceans with large seasonal and inter-annual fluctuations in ice-cover and ice transport. The location of the ice edge during summer can vary by hundreds of kilometers from year to year (Gloersen *et al.*, 1992), and there is also variability on time scales extending to centuries, correlated with the North Atlantic Oscillation (NAO) (Vinje, 2001). These variations reflect the inter-annual dynamics of inflowing Atlantic water and atmospheric forcing. This large variability makes the MIZ an ideal location to examine the expected consequences of long-term changes in ice conditions expected as a result of climatic warming. In the northern Barents Sea the MIZ is also ecologically important because it represents one of the highest production areas in high-Arctic water masses. The high bioproduction is due to several factors including (1) high annual primary production in close association with the receding ice edge and strong mixing following the breakdown of a previously stratified water column, (2) advection of large herbivorous zooplankton from the Norwegian Sea into the Barents Sea, and (3) transport of ice fauna by the Transpolar Drift from the Arctic Ocean into the Barents Sea where organisms are released during the melting process.

The primary production associated with the MIZ, which in the Barents Sea Polar Front area is typically between 40 and 50 g C m^{-2} yr^{-1} (Rey *et al.*, 1987; Wassmann and Slagstad, 1993; Hegseth, 1998) and consists of three components; a) actively growing phytoplankton at the outer edge of the ice margin and in larger leads; b) a layer of specialized ice algal assemblage in pack ice; and c) a sub-ice algal assemblage associated with multi-year ice (Syvertsen, 1991; Melnikov, 1997; Falk-Petersen *et al.*, 1998; Hegseth, 1998). Further north, a greater proportion of production takes place in ice rather than in water. The onset of the pelagic primary production is directly related to the seasonal availability of incident light and melting of the ice (Sakshaug and Slagstad, 1991), while the ice-related production is dependent on light only (Hegseth, 1992) and ceases as the ice melts. The annual primary production is coupled to the spatial variation in ice cover, and hence will vary between warm and cold years (Slagstad and Stokke, 1994). The ice algae also represent the basis of the food chain. Ice algae are utilized by a variety of metazoans living within the brine channel system of the sea ice and by crustaceans living closely associated to the ice underside (Spindler, 1994; Gradinger *et al.*, 1999; Werner and Gradinger, 2002). These in turn are important food items for higher trophic levels, such as polar cod, seals and polar bears. The trend towards a decreased extent and thickness of the sea ice cover in the Arctic (Rothrock *et al.*, 1999; Wadhams and Davis, 2000) poses serious threats to ice-related organisms that are dependent upon the physico-chemical environment provided by sea ice. Additionally, the effects on higher trophic levels of the Arctic ecosystems could be dramatic if the partitioning of the primary production between ice-related and pelagic components changes. Less ice may lead to less pronounced melt water layer, and possibly earlier melting (Stabeno and Overland, 2001). This will influence the timing and duration of the pelagic spring bloom (Engelsen *et al.*, 2002) and the match-mismatch between primary and secondary production (Slagstad and Støle-Hansen, 1991; Falk-Petersen *et al.*, 1999). It will also influence the sedimentation of the spring bloom, and hence, the benthic communities.

Benthic communities in the Arctic are dependent on sedimentation of organic matter from the overlying water column for energetic requirements. The general paradigm is that a spring phytoplankton bloom results in a seasonal pulse, of short duration but high magnitude, of organic material to the benthos, i.e. strong benthic-pelagic coupling (Petersen and Curtis, 1980; Sakshaug and Skjoldal, 1989; Grebmeier and Barry, 1991; Steele, 1991; Grebmeier *et al.*, 1995; Hobson *et al.*, 1995; Wassmann *et al.*, 1996; Piepenburg, 2005). The amount and quality of organic material reaching the benthos is dependent on several interrelated factors including the timing and overall magnitude of synthesized organic matter, local advection by currents and the efficiency of grazing by herbivorous zooplankton. The latter essentially determines how the available primary production is partitioned between the pelagic and benthic systems (Mitchell *et al.*, 1991; Sakshaug, 1991). Zooplankton grazers that are tightly coupled to the phytoplankton bloom, as often seen in areas not influenced by ice, can drive a food web towards fish and bird production, whereas the absence of such grazers leads to benthic-pelagic coupling and a food web dominated by the benthos (Carroll and Carroll, 2003).

However, such a paradigm is not adequate for heavily ice-covered Arctic seas where a substantial portion of the local primary production is due to ice-associated algae. Ice-algae have been shown to act as an early-season carbon source that initiates biological production prior to significant phytodetritus flux (Ambrose Jr. and Renaud, 1997; Rowe *et al.*, 1997; Stabeno and Overland, 2001). Studies from the Chukchi Sea (Ambrose & Clough, unpublished data) and Bering Sea (Stabeno and Overland, 2001) suggest that the duration of ice cover strongly affects the timing of the spring bloom, the predominant source of primary production (ice algae vs. phytoplankton) and amount of local primary production made available to the benthic community. In heavy ice years, an early ice-associated spring bloom occurs and a larger fraction of the total production is due to ice algae rather than pelagic phytoplankton. Early-season herbivorous zooplankton and ice fauna are less abundant and do not graze ice algae efficiently, resulting in a large export of primary production to the benthic community. In contrast, in years with less ice, ice algae are of less importance and open water phytoplankton blooms dominate the local primary production. The zooplankton community matched to a later-occurring bloom efficiently grazes such pelagic-dominated production, essentially retaining much of the production in the water column and resulting in less carbon export to the bottom (Carroll and Carroll, 2003). Stabeno & Overland (2001) have documented a major shift in the Bering Sea shelf ecosystem in the 1990s from a pelagic to a benthic focus related to such top-down effects, as well as an earlier spring transition due to climate change.

It has been recognized that a sound elucidation of the ecological effects of climate-induced environmental changes requires a combination of long-term data collection (Soltwedel *et al.*, 2005), process-oriented studies on the mechanisms driving the changes and modeling efforts allowing for predicting the effects.

The investigations proposed in IPY-CARE are related to other on-going/planned research programmes, such as SPACES (Synoptic Pan-Arctic Climate and Environment Study), HERMES (Hotspot Ecosystem Research on the Margins of European Seas – the Nordic Margin), MarBEF (Marine Biodiversity and Ecosystem Functioning), DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies), COBO (Coastal Ocean Benthic Observatory).

Research Plan

WP2.1 Primary production and vertical export

Partners: Wassmann (NCFS), Backhaus (UH), Masque (UAB)

Tasks*:* To determine the response of *in situ* phytoplankton production, biomass, and diversity and flux of sedimenting material to climate variability and to explore the relationship between phytoconvection, vertical mixing, phytoplankton growth, spring bloom biomass, and vertical flux attenuation

Methodology / work description:

The analysis will include *in situ* investigations along open water/marginal ice zone gradients during different seasons. Vertical stratification and diffusion as well as nutrient, suspended biomass, vertical export of biogenic matter and ^{234}Th inventories will be carried out on all cruises applying state of the art technology. Phytoplankton biomass and species composition will be determined in late winter, while a more intensive programme will be applied in spring and summer, including quantification of phytoplankton diversity and biomass, TEP/DOC, assessment of *in situ* primary production and sampling of suspended/sedimented solids. ^{234}Th calibrated sediment traps will be exposed in the twilight zone, and data on particulate and total carbon and nitrogen will be compared with the ^{234}Th inventory. Microbial degradation and zooplankton experiments will be carried out to understand the attenuation of vertical flux related to vertical mixing and bloom dynamics. A coupled phytoplankton-convection model will be applied to selected late-winter profiles of suspended biogenic matter, phytoplankton and vertical export. Simulations with realistic forcing will extrapolate observations towards spring to estimate whether a spring bloom inoculum was supported by convection, how key phytoplankton species contribute to the bloom and how vertical export of biogenic matter is regulated. The algorithms of the physically-biologically coupled 3D model will be re-evaluated, and the suspended biomass of key phytoplankton species, primary production and vertical exports will be validated (see also WP2.5).

WP2.2 Effects of varying climate on community structure, biological processes, and energy flux

Partners: Piepenburg/Spindler/Werner (IPOE/ASM), Soltwedel (AWI), Falk-Petersen/Hop (NPI), Carroll (APN), Weslawski (IOPAS), Sirenko (ZIN), Melnikov (SIO)

Task*:* To determine how a changing climatic regime drives primary production in the Arctic through different dominant carbon sources (i.e. ice algae vs. phytoplankton) and its concomitant effects on the biological carbon and energy transport in sympagic, pelagic and benthic systems

Methodology / work description:

The research methodology is highly interdisciplinary and combines analyses of data available from databases and ongoing programmes (historical time series), collection of novel data in field studies, including the use of innovative lander technology, ROVs and AUVs (also operating under the ice), experimental laboratory and in-situ process studies and modelling work in order to achieve a comprehensive quantitative understanding of key interactions between sea ice, ocean and seabed and of the mechanisms that regulate them. We will explore how biological processes influence energy flux pathways by the use of lipid biomarkers and stable isotopes. Changes in community and size structure of the sympagic, pelagic and benthic communities will be studied by the collection of new data over four seasons and the analysis of data available from databases and ongoing programmes. Carbon demand will be budgeted in order to quantify major pathways of the carbon and energy flux in sympagic, pelagic and benthic systems. The data will be used to develop a conceptual ecosystem model and numerical process models (see WP2.5) to quantify the integral effects of different climate regimes on the system, whereas laboratory experiments will study the responses of biological processes to climate change. Historical data will provide time series, which can improve our understanding of how they co-vary. The conceptual ecosystem model, various time series of secondary production, and numerical modelling will be used in the socio-economic impact assessment.

WP2.3 Arctic sea ice biogeochemistry

Partners: Tison/Lancelot/Chou (ULB), Melnikov (SIO), Stefels (RUG), Thomas (UWB)

Task**:** To evaluate the modalities and the level of contribution of sea ice biota to marine fluxes of gases of climatic significance and their sensitivity to climate dynamics and variability

Methodology / work description:

Significant physical, chemical and biological processes in Arctic sea ice, as well as interactions with the ocean, cryosphere, land and biosphere need to be better quantified and included in the modelling work. Target candidates for ocean-sea ice-atmosphere-climate interactions are CO_2 and dimethyl sulphide (DMS), both being actively involved in sea ice microbial metabolism. The efficiency of the latter appears to be controlled by the availability of micro-nutrients, such as iron. Our research programme includes field investigations, experimental laboratory process studies and modelling. *Field work* will concentrate on the sea ice core database acquisition to characterize the distribution of Fe, CO_2, DMS and other fundamental physico-chemical and biological parameters in sea ice, snow and interface water below. We will also attempt to measure CO_2 and DMS fluxes at the ice surface. In addition, chemical transformation of iron during sea ice melting and the associated biological and chemical processes will be examined. *Experimental laboratory studies* on cultures of polar micro-organisms will focus on the a) mechanisms regulating iron bio-availability and the iron isotopes bio-signature, and b) stress-dependency (light, temperature, nutrients) of DMSP/DMS production for various assemblages. Each topic involves the development of novel analytical techniques. *Modelling effort* will focus on the development of a new sea ice biogeochemical model, the parameterization of which being obtained from the field and process-level results. It aims at producing a comprehensive dataset of Arctic ocean-atmosphere CO_2 and DMS fluxes, which will ultimately serve as input to the models of WP2.5, as well as WP1 and WP3.

WP2.4 CO_2 air-sea exchange

Partners: Anderson (UGOT), Johannessen (UoB), Børsheim (IMR), Makshtas (AARI)

Task: To determine the response of CO_2 air-sea flux in Arctic waters to changes in biological activity caused by climate variability

Methodology / work description:
A combination of fieldwork and theoretical evaluation will be performed. Fieldwork includes measurement of the carbon system during cruises in order to determine the surface water CO_2 partial pressure (pCO_2) in relation to the biological conditions (determined mainly under WP2.1) in regions of variable ice cover. These data will be evaluated together with historic data. Examples of effects by the biological system on the pCO_2 of the surface water are: A decrease in the ice cover effects the depth of the surface mixed layer, the light conditions and the mixing energy by wind forcing. An increased runoff affects the supply of nutrients (and other chemical constituents) and stratification, as will any change in the inflow of waters from the surrounding oceans. The quantification of the biological carbon pump in historic times (the last ~50 years) will be evaluated by fitting functions of deep-water data of the carbon system, nutrients, oxygen to transient tracers. This will be performed on different isopycnal surfaces within different regions (water masses) to ensure that mixing of water masses does not bias the evaluation. All evaluation will be done in close collaboration with activities in WPs 2.1 to 2.3. Furthermore, both historic and novel data of the carbon system will be used to initialize model runs and to test the model output of WP 2.5 and WP1.6, including regional air-sea fluxes and export production estimates. Once the model performs to satisfaction with regard to the carbon system, different forcing will be used to evaluate the climate effect on the carbon cycle.

WP2.5 Ecosystem modelling and carbon flux

Partners: Slagstad (SINTEF), Wassmann (NCFS), Backhaus (UH), Tison (ULB), Anderson (UGOT), Drange (NERSC/BCCR)

Task: To simulate change in carbon flux (primary production, vertical export and air-sea exchange of CO_2)

Methodology / work description:
This task serves as a focal point of the ecological modelling efforts of WP2 and has close ties to WP1 and WP3 which focus on the modelling of physical processes. Carbon fixation (primary production) and its fate through biological transformation (grazing, sinking and bacterial activity) along the marginal ice zone will be simulated by means of an existing coupled 3D hydrodynamic and ecological, 4 km grid size model, which is nested into a large-scale model covering the Arctic Ocean and the Nordic Seas. Using data and process knowledge contributed by all WP2 partners, the ecological model will be validated and further developed, including three key mesoplankton species, vertical flux regulation in the twilight zone, and a high-resolution grid to investigate mesoscale processes near the ice edge. An integrated CO_2 module calculating the air-sea flux of CO_2 as a result of physical and biological processes will be validated and refined in close collaboration with WP2.3, WP2.4 and WP1. In addition, the impact of the algal seeding stock (e.g. resting spores overwintering at the bottom and brought to the surface through vertical convection during late winter) for the onset and development of the phytoplankton spring bloom is of special interest. As climatic change is likely to alter the vertical convection, this process will be studied through convection models (see WP2.1) that will also provide input for the ecological model.

WP3 Air–sea–ice processes and climate variability

WP-leader: J.-C. Gascard (LODYC); co-leader B. Rudels (FIMR) and P. M. Haugan (UoB)

Objectives

The overall objective is to investigate selected air-sea-ice processes of important for the climate in the Arctic, as discussed in WP1. WP3 will address four categories of processes: (1) The thermohaline circulation in the Nordic Seas; (2) Deep convection and deep water formation in the Greenland Sea; (3) Brine formation on shelves and polynyas and ventilation of the deep Arctic basins; and (4) Atmosphere, ocean, sea-ice interaction processes in the High Arctic.

Research Plan

WP3.1 Important aspects of the thermohaline circulation in the Nordic Seas

Partners: Mork (IMR), Piechura (IOPAN), Gascard (UPMC/LODYC), Döscher (SMHI), Lavrenov (SRC AARI)

Task: Study the cooling and freshening of Atlantic water masses inshore (along the continental slope) and offshore (along the Arctic front) and interactions with Polar waters during transit across the Nordic Seas, the northern limb of the THC.

Methodology / work description
Based on field experiments and models, we propose to study the transformation by cooling and freshening due to internal (tidal) mixing or eddy diffusivity of Atlantic waters entering the Nordic Seas and their interactions with polar and coastal currents (Jan Mayen and North-East Icelandic Polar Currents, Norwegian

Coastal Current) during their transit to the Arctic Ocean. We will use Lagrangian techniques (drifting and profiling floats) all year around in addition to hydrological surveys (including tracers and radionuclides) once a year at least, or twice on some instances to measure water mass physical parameters (CTD), currents (tidal, inertial, sub-meso- and meso-scale). We will also run models with data assimilation and/or prescribed boundary conditions to compare with real observations and make the appropriate corrections in models and/or proposed new parameterisations for large-scale models (vertical and horizontal eddy diffusivity). Strong links with WP1 will be established.

WP3.2 Deep convection and deep water formation in the Greenland Sea

Partners: Backhaus (Uni-Ham), Gascard (UPMC/LODYC), Wadhams (UCAM-DAM), Uscinski (UCAM-DAM), Rudels (FIMR), Alekseev (SRC AARI)

Task: Study the variability of deep convection and deep water formation and evolution in the Greenland Sea and integrated effects of sub-mesoscale coherent vortices on deep water mass formation and THC in the Nordic Seas. Origin(s) of the North Atlantic overflows.

Methodology / work description:

The time history of the deep water renewal in the Greenland Sea and its dependence on atmospheric forcing will be analysed based on extensive existing data sets. The discovery of long-lived sub-mesoscale coherent vortices (SCV) in the Greenland Sea during wintertime has opened new avenues for what concerns deep convection and how it is related to the global THC. In this task we propose to: (1) continue to survey these long-lived features in order to better understand their origins and their fate and (2) their integrated effects on the general circulation in the Nordic Seas. Interactions of SCVs with the surface mixed layer will also be considered in a modelling approach. Non-hydrostatic models will also be developed in order to learn more about the geophysical fluid dynamics associated with these SCVs, but also to propose some parameterisation for large-scale models which cannot take SCVs explicitly into account due to their sub-grid scale. Dedicated field experiments will be organised making use of new technologies mainly based on Lagrangian techniques (profiling floats).

WP3.3 Brine formation on shelves and polynyas and ventilation of the deep Arctic basins

Partners*:* Huthnance (POL), Haugan (UoB), Quadfasel (Uni-Ham), Shapiro (UoP), Willmott (POL), Döscher (SMHI), Rudels (FIMR), Heygster (UB), Gascard (UPMC/LODYC), Lavrenov (SRC AARI), Morison (APL/UW), Inall (SAMS)

Tasks: (1) Perform dedicated field experiments for studying first, processes and mechanisms leading to brines production and second, variability of sinking plumes at the continental slope and related mixing with ambient waters; and (2) perform detailed modelling of polynya formation, brines production, dense water outflows at shelf break (cascades) in the Marginal Ice Zones and along the continental margin, turbulence and mixing. Specific objectives are to: (a) create polynya parameterisations for large-scale models; (b) validate shelf-and-slope models' representation of dense shelf-water formation, overflow, turbulence and mixing on the continental slope; (c) evaluate the sensitivity to both ambient and initial conditions; (d) apply validated models to infer fluxes in areas with scarce observations; and (f) estimate cascading fluxes and their contribution to oceanic water masses.

Methodology / work description:
In the Arctic, dense water formation and deep ocean ventilation are frequently associated with the production of brines as a result of winter ice growth over the shelf polynyas and in the marginal ice zone. Dense water formation (with a salinity of 32.85 psu) in Arctic polynyas has been estimated at 0.7-1.2 Sv, and high salinity shelf water, with densities comparable to that of the deep Arctic, is produced in the Barents and Laptev seas, with a total amount of up to 3 Sv produced on the Arctic shelves. Because of the sparsely observations and the difficulty of representing these small-scale features in current models, our understanding of polynya and the associated brine production processes is limited. Interannual variability of ice growth in polynyas, and hence of brine production rates, is large. This variability is strongly linked to regional and large-scale weather patterns, but the detailed mechanisms are not well understood. There is also great uncertainty as to the relative contribution of brines formed in shelf polynyas to the cold Arctic halocline, intermediate and deep Arctic waters. The work will require dedicated field experiments as well as detailed modelling of processes where use of remote sensing data is included from WP5.2.

WP3.4 Atmosphere, ocean, sea-ice interaction processes in the High Arctic

Partners: Rudels (FIMR), Wadhams (UCAM-DAM), Björk (UGOT), Gascard (UPMC/LODYC), Vihma (FMI), Zilitinkevich (Uni-Helsinki), Fichefet (UCL-ASTR), Döscher (SMHI), Bruemmer (Uni-Ham), Wacker (AWI), Heygster (UB), Ezraty (IFREMER), Laxon (UCL), Lavrenov (SRC AARI), Esau (NERSC), Haugan (UoB), Morison (APL/UW), B. Ivanov (AARI), Wilkinson (SAMS), Hughes (SAMS)

Task: Investigate the perennial ice cover and its dependence on radiation and on the advected and convective heat fluxes in the atmospheric and oceanic boundary layers. The studies includes internal mixing processes in the ocean, the heat transfer between the Atlantic layer, the halocline and the polar mixed layer and the interaction between different gyres and inflow branches.

Methodology / work description:
We propose to study the mechanisms controlling the stratification of the atmospheric and oceanic boundary layers in the High Arctic from existing data sets, large- and mesoscale models, and new observations. We will study the cloud radiative forcing, heat fluxes above heterogeneous surfaces including marginal ice zones, large-scale horizontal heat advection, and also address special conditions such as cold air outbreaks and Polar lows, the interactions between sea ice and the underlying waters and the evolution of the polar mixed layer and the halocline and their communication with Atlantic and Pacific waters. An Arctic Observatory system based on new technologies will be created, allowing for process oriented experiments. The Arctic perennial ice deserves special attention due to the considerable variability (thinning) that has been observed recently over a large domain of the Arctic Ocean. Here not only remote sensing but also the Arctic observatory system will be vital. The Arctic observatory system is also a main part of the WP5 Tasks.

WP4 Past climate variability

WP-leader: R. Spielhagen (ASM/IFM-GEOMAR), co-leader: N. Koc (NPI)

Objectives

The main objectives are to determine the past variability and changes in the Arctic climate system during the Holocene and to improve their representation in regional and global (paleo) climate models. This requires a significant extension of the presently available data base, which can be achieved by additional sampling, refinement of old and development of new analytical methods and climatic proxies, and a close cooperation between paleoclimatologists and paleoclimatic modellers.

Approach

The most important role of marine and glaciological paleo data is that they provide long-term evidence of climate change in the past. Marine and glaciological paleo data has revealed that the strength of the THC during the deglacial and the present warm period ("Holocene") was highly variable. Even during the last 8000-9000 years, which had been previously assumed to be climatically stable, severe climatic variations on decadal to millennial time scales have been found, the causes of which remain uncertain. These variations, including the termination of the last glacial period, imply fundamental changes in the THC, primarily in the Nordic Seas. Presently, leads and lags of changes and events between the Arctic and North Atlantic oceans cannot be substantiated. Therefore, it is critical to identify the nature and strength of these linkages in order to understand the dynamics and the risk of rapid changes.

Selected time period

The Holocene period (last 10,000 years) has been selected for analysis, mainly because i) it closely resembles modern conditions, ii) it has a well-defined range of natural climatic variability, iii) its variability is to a certain amount cyclic in behaviour, iv) it contains rapid climate change events, and v) it offers good possibilities to test prognostic models. A special emphasis will be laid on the climatic variability of the last 1000 years, because for this period a record of historical climate data as well as direct climate observations and instrumental data are available which allows a calibration of paleoclimatic proxies and an improvement of paleoclimatic models by hindcast simulations.

Reconstruction of marine, terrestrial, and atmospheric conditions from proxy data

The main parameters determining the Arctic climate and their Holocene variability shall be reconstructed from a variety of proxy data. The reconstruction should be performed both as time series and for selected time slices. The nature of the variable types of archives determines the time resolution that can be achieved from each archive (millennial to seasonal). At least a centennial-scale resolution is desirable for the archives utilized in WP4. Regional differences have to be elaborated. An important aspect of the work must be the determination of natural magnitudes of change which define the envelope of natural variability in the Arctic climate system, the establishment of a baseline of pre-industrial Arctic climate conditions, and an evaluation of the role of the Arctic Ocean and Arctic ice sheets and glaciers as an early warning system for widespread climate change.

Arctic Sea ice cover

The most important parameter determining the Arctic Ocean climate is the area extension and density of the sea ice cover. This ice cover is presently decreasing both in extension and thickness. Available low-resolution data from the eastern and central Arctic Ocean (Nørgaard-Pedersen *et al.*, 1998; 2003) suggest a less dense ice cover during the middle Holocene. WP4 seeks to reconstruct the variable position of the sea ice margin through time with highest possible time resolution, especially in the Arctic Gateway (Fram Strait) and the Greenland Sea. These areas are of special interest because of their proximity to the area of present-day deepwater formation and the surface water inflow of relatively warm and saline Atlantic Water. In this context, the relationships between regional oceanic parameters (water salinity, temperature, currents), atmospheric parameters (air temperature, pressure fields, wind directions), the river runoff from surrounding continents, and the sea ice cover are of special interest and should be investigated by coupled models.

River water inflow and Freshwater export

The river water runoff from the surrounding continents into the Arctic Ocean is marinating the low-salinity surface water layer of the Arctic which characterizes the well-stratified upper part of the Arctic Ocean water column. Furthermore, it strongly supports the formation of the sea ice cover. Coupled models indicate a strong influence of the Arctic freshwater export on the intensity of the global thermohaline circulation (THC). On the other hand, there is a strong coupling between oceanic evaporation, atmospheric transport of heat and moisture, and the river runoff. Available data from Siberian shelf seas indicate a significant Holocene variability of the river runoff (Matthiessen *et al.*, 2000; Bauch and Polyakova, 2003; Polyakova and Stein, 2004; Stein *et al.*, 2004). For a better understanding of the natural variability of the coupled system, it is necessary in WP4 to obtain high-resolution proxy records from marine sediment cores from the Arctic Ocean and the area of freshwater and sea ice export, which allow to reconstruct changes in ocean salinity, stratification, and freshwater export. If such records can be precisely correlated to river runoff records, they will strongly improve our knowledge about possible natural leads and lags of changes. Such leads and lags may be induced by inertia effects (e.g., from residence times of the freshwater component). The application of coupled ice-ocean models will help to determine regularities in the system and detect anthropogenic influences in the recent past.

Heat transport to the Arctic

Oceanic heat transport to the Arctic mainly occurs through the advection of saline Atlantic Water, which enters the Arctic through the Arctic Gateway and across the Barents Sea. There is evidence that this northward advection has varied within the Holocene, but it is not clear whether changes were cyclic or more random (Risebrobakken *et al.*, 2003; Sarnthein *et al.*, 2003). Using a variety of proxies from marine sediment cores available for Atlantic Water influence, work in WP4 will be directed to solve this problem. High-resolution records of Atlantic Water advection in both inflow areas have to be established to investigate the Holocene natural variability of heat transport to the Arctic Ocean. In the reconstructions and time series, bathymetric changes from isostatic crustal rebound in the Barents Sea have to be taken into account. A precise correlation to the records of changes in ice coverage and freshwater runoff and the involvement of coupled models will allow investigating the relationships of these parameters in close detail. Atmospheric heat transport to the Arctic is strongly related to the prevailing atmospheric flow patterns which are known to vary on short- and medium-term timescales (NAO, AO). It is a goal of WP4 to reconstruct the variability of these current patterns based on terrestrial data on longer timescales and compare it to the variability of oceanic heat advection.

Biological productivity and oceanic carbon fluxes
Biological productivity, a major factor determining carbon fluxes in the Arctic atmosphere-ocean system, is strongly dependant on parameters such as ice coverage, water temperature, and nutrient supply from river influx. All these parameters have shown a significant variability in the past and are presently undergoing a rapid change. To establish a baseline of pre-anthropogenic conditions and natural variability in the past, and to understand the ongoing change in Arctic biological communities and productivity, it is necessary to determine Holocene changes of biological productivity and carbon fluxes in the Arctic Ocean. The results should be linked to the natural climate variability as expressed in the variability of the individual environmental parameters influencing the marine biological system. The major question is how climate has affected ocean productivity in the last 10,000 years.

Ice sheets, glaciers and terrestrial systems
Ice sheets and glaciers are active players as well as passive archives of the Arctic environment. They are directly influencing the regional climate by their area extension, their height, and their release of meltwater and icebergs (if they reach the sea). On the other hand, they represent archives of atmospheric activity (precipitation and heat advection) in the area. The Arctic glaciers and ice caps have a rapid response time to climate change and are believed to contribute more to sea level rise over the next hundred years than Greenland and Antarctica. It is therefore important to understand the current and future volume changes (mass balance) on these ice caps. In WP4 the history of ice sheets and glaciers in the Eurasian Arctic and on Greenland will be analyzed to reconstruct glacier sizes, winter precipitation, and freshwater runoff. Linkages to the oceanic and atmospheric heat transport have to be established.

Climate forcings, feedbacks, and linkages

In our understanding of natural Arctic climate variability there are still many gaps concerning the linkage of climate forcing factors and changes in the Arctic environment. Forcing factors may involve both external influences (e.g., insolation, volcanoes) and climate changes caused by developments in the lower latitudes and transferred to the Arctic, e.g., by changes in the intensity of the North Atlantic Drift. It is a main goal of WP4 to determine the main forcings shaping the Holocene Arctic climate, the mechanisms by which the forcing factors were directly influencing Arctic environmental parameters, and the feedbacks between the Arctic environmental variability and forcings originating in lower latitudes. Linkages between developments on land and in the ocean have to be documented and analyzed for leads and lags to determine internal feedbacks within the Arctic climate system. This includes both reversible linkages (sea ice coverage vs. river runoff) and changes which were largely unidirectional in the Holocene (e.g., coastal erosion, thawing of permafrost). Furthermore, possible trends in the development of such linkages have to be determined.

The application of paleoclimatic models (AOGCMs) will play a central role in WP4 to assess the complex of forcings, responses, feedbacks and linkages in the Arctic climate system. They will be used to determine and understand how and where forcings were interfering with the atmosphere-ocean system in the Arctic and how, by feedbacks and coupled responses, the forcing was further spread to reach all major constituents of the system. Possible trends or variabilities in the feedback mechanisms and coupled responses within the Holocene should be identified. In turn, paleoclimatic data sets will be available for validating model results and improving the models. Finally, the models may be used to identify possible "hot spot areas" where, according to the model results, magnitudes of changes in the paleoenvironmental system were strongest and/or may have been recorded in extraordinary high resolution.

Technical tasks

To achieve the envisaged progress in our understanding of natural variability in the Arctic, a number of technical goals have to be reached. Reaching these goals is a prerequisite to establish the necessary data base of paleoclimatic variability in the Arctic which defines the baseline of natural variability and allows a clear detection of anthropogenically induced climate and environmental change. The most important goals are as follows:

- Suitable sites must be detected where high-resolution archives of Holocene environmental parameters can be obtained. This includes sediment cores from continental shelves, slopes and selected deep-sea areas, as well as Arctic lakes, ice cores, and terrestrial archives of glacier sizes and activities.
- A data base of Arctic paleoclimate proxy data from archives (marine and terrestrial sediments, glacier ice) and data banks must be generated as a basis for the analysis of natural climatic variability in the Arctic and a test case for paleoclimatic models.
- Techniques for quantitative and semiquantitative reconstructions of physical oceanic and atmospheric parameters from paleoclimate proxy data must be developed and improved by calibration. The parameters include Atlantic Water advection, freshwater export, modified Atlantic Water export, summer and winter sea ice margins, average annual duration of ice coverage, ice drift patterns, ocean salinity, ocean temperatures, air temperatures, precipitation, atmospheric circulation patterns, sea level, particle fluxes (biogenic, terrigenic, carbon, etc.).
- Atmospheric and oceanic parameters must be reconstructed for the Holocene to analyze their variability (amplitudes, cycles) on subannual to millennial timescales and their feedbacks with forcing factors, and to elaborate regional differences and linkages to lower latitude developments.
- GCM simulations of the last 1000 years must be performed with fully coupled ice-ocean-atmosphere models.
- Model results must be compared with paleoenvironmental reconstructions to analyze climatic modes and the contribution of different forcings.
- The response of atmospheric and oceanic parameters to forcings under different climate regimes must be studied from paleoclimatic reconstructions and models for critical periods such as the Mid-Holocene climatic optimum (ca. 8-5 ka), the Medieval climatic optimum (ca. AD 900-1300), and the "Little Ice Age" (ca. AD 1600-1850).
- A baseline of pre-industrial Arctic climate conditions must be established/defined to detect a possible anthropogenic influence on Arctic climate in Late Holocene parts of the records.

Research Plan

WP4.1 Establish proxy data time series from paleoclimatic archives and data banks

Partners: Spielhagen (ASM/IFM-GEOMAR), Bolshiyanov (SRC AARI), Knudsen (UAAR), Stein (AWI), Jansen (BCCR), Mikkelsen (GEUS), Koç (NPI), Masque (ICTA-UAB), Moore (UoL), Hald (UiT)

Task: To generate a data base of Arctic paleoclimate proxy data from archives (marine and terrestrial sediments, glacier ice) and data banks as a basis for the analysis of natural climatic variability in the Arctic and a test case for paleoclimatic models
Methodology / work description:
Samples from various paleoclimatic archives in the Arctic (ice cores, sediment cores from lakes, fjords, and continental margins) will be analysed which are already available or which will be obtained mainly in 2004/05, using various geochemical, sedimentological, micro-paleontological, and radiometric methods. We will concentrate mainly on northern Greenland, Svalbard, the Fram Strait, the adjacent Eastern Arctic Ocean, and northeastern Eurasia. Only high-resolution archives with annual to centennial scale resolution and suitable data from data banks will be used. The results will represent proxy data time series for Arctic climate change in the last 10 000 years (10 ky), with special emphasis on the last 1 ky. Age determinations will be based predominantly on radiometric methods, but other methods (e.g., annual layer counting) will be used where applicable.

WP4.2 Develop transfer functions for semi-quantitative and quantitative reconstructions

Partners: Koç (NPI), Bolshiyanov (SRC AARI), Knudsen (UAAR), Spielhagen (IFM-ASM/GEOMAR), Stein (AWI), Jansen (BCCR), Mikkelsen (GEUS), Masque (ICTA-UAB), Moore (UoL), Hald (UoT)

***Task*:** To develop and improve techniques for quantitative and semi-quantitative reconstructions of physical oceanic and atmospheric parameters from paleoclimate proxy data
Methodology / work description:
Based on state-of-the-art techniques (physical and chemical relationships, modern-analog techniques, biomarkers, others) methods will be developed or improved to (semi)-quantitatively transfer proxy data to physical oceanic and atmospheric parameters (water and air temperatures, sea water salinities, ice coverage, current directions, freshwater export, carbon budgets, etc.). Modern and historic data sets elaborated by WP1, WP3 and WP5, will be used for calibration purposes.

WP4.3 Reconstructions of paleoclimatic and paleoceanographic parameters

Partners: Stein (AWI), Bolshiyanov (SRC AARI), Knudsen (UAAR), Spielhagen (ASM/IFM-GEOMAR), Jansen (BCCR), Mikkelsen (GEUS), Koç (NPI), Rosell-Mele (ICTA-UAB), Moore (UoL), Hald (UoT)

***Task*:** To reconstruct atmospheric and oceanic parameters, to analyse their variability and feedbacks with forcing factors, and to elaborate regional differences and linkages to lower latitude developments
***Methodology / work description*:**
Transfer functions developed in WP 4.2 will be applied to analyse the variability of

atmospheric and oceanic parameters (e.g., ocean and atmospheric temperatures, ocean salinities and density fields, precipitation, freshwater export, ice coverage, currents) in the working area during the last 10 ky (Holocene). Regional differences will be elaborated. Data series will be analysed statistically for cycles, trends and paleoclimatic descriptions and definitions of "end member" states of natural climatic variability. Of special interest are the role and sensitivity of the Arctic Ocean and its interaction with the North Atlantic in Holocene climatic changes, including short-term fluctuations. Linkages to short-term climate fluctuations at lower latitudes (incl. tropics) will be determined, with special emphasis on leads and lags between Arctic and lower latitude climatic developments. Feedbacks with external forcing factors will be identified for long (10 ky) and short time series. The response of atmospheric and oceanic parameters to forcings will be identified for defined time slices (Mid-Holocene climatic optimum, ca. 8-5 ka; Medieval climatic optimum, ca. AD 900-1300; "Little Ice Age", ca. AD 1600-1850). A baseline of pre-industrial Arctic climate conditions will be established.

WP4.4 Simulations with coupled ice–ocean–atmosphere models, both GCMs and EMICs

***Partners*:** Jansen (BCCR), Stein (AWI), Drange (NERSC), Goosse (UCL-ASTR)

***Task*:** To perform GCM simulations of the last 500-10,000 years with coupled ice-ocean-atmosphere models

***Methodology / work description*:**

Simulations will be performed over the last 10 ky, with special emphasis on the last millennium using both fast Earths System Models of Intermediate Complexity (EMICs) and state-of-the art, fully coupled AO-Sea Ice GCMs, driven by both natural and anthropogenic forcings (solar irradiance, effect of volcanic eruptions, human-induced GHGs and aerosols). The numerical experiments will be done in ensemble mode in order to estimate precisely the role of the natural variability of the system. Results will be compared to the ones of long control experiments carried out with the models and analysed in order to understand the natural and forced variability at decadal to millennial time-scales in the Arctic. A particular focus will be on a potential polar amplification of both natural and forced climate variations. A small number of simulations with a state-of-the-art, fully coupled ice-ocean-atmosphere model over the last 500 years will be performed to check the consistency of these results with the one of the low-resolution models, and to test the sensitivity of the results to the initial conditions.

WP4.5 Analysis of control and scenario integrations

Partners: Goosse (UCL-ASTR), Bolshiyanov (SRC AARI), Knudsen (UAAR), Spielhagen
(ASM/IFM-GEOMAR), Stein (AWI), Jansen (BCCR), Mikkelsen (GEUS), Drange (NERSC), Koç (NPI), Rosell-Mele (ICTA-UAB), Moore (UoL), Hald (UoT)

***Task*:** To compare model results with paleoenvironmental reconstructions and to analyse climatic modes and the contribution of different forcings

***Methodology / work description*:**

Results of paleo-environmental reconstructions and model results will be compared in order to test how models are able to reproduce the observed evolution of the Arctic climate. The history of major modes of climatic and oceanic variability (e.g., AO, NAO) and the relative contribution of natural and forced variability in the evolution of those modes will be assessed. In particular, the model/data comparison will be used to verify if the magnitude of past low-frequency variations (>50 years) is well simulated, a necessary condition for the attribution of any observed climate change to human activities. If the model underestimates or overestimates those low frequency variations, it will be checked if it is due to a misrepresentation of natural variability or of forced variability, and thus maybe of the forcing. In such a case, improvement will be proposed. The conclusions derived from those analyses will be compared to the one obtained for the 20th and 21st century in WP1. Where necessary, the validity of transfer functions from WP4.2 will be re-assessed. The role of the Arctic Ocean and the Greenland ice sheet as a possible early warning system for climate change will be defined.

WP4.6 History of the Arctic climate in the 19th century and the beginning of the 20th century based on early instrumental data

Partners: Przybylak (NCU), Overland (PMEL/NOAA), Lagun (AARI), Nordli (met.no), Kohler (NPI), Isaksson (NPI), Majorowicz (NG and UND), Araźny (NCU), Vizi (NCU)

Task: To generate a meteorological and climate-related (water temperature, sea-ice extent and thickness etc.) data base for the Arctic from published and unpublished sources using an early instrumental (19th century and the beginning of the 20th century) land and marine observations, to describe historical climate and its natural variability, and to compare the historical and modern Arctic climates.

Methodology/work description:

Historical data available mainly in libraries and archives located in different institutions in Canada, the USA, Great Britain, Norway, Sweden, Denmark, Russia etc. will be collected. Standard climatological methods (including quality control and homogenisation methods) will be used to check (data quality) and to conduct calculations of a number of statistics needed to describe climatic conditions. Both time and spatial changes of different climate and environmental variables will be investigated. Arctic climate reconstructions based on proxy data and inversions of equilibrium well temperature logs will be compared with the early instrumental data. Similarities and differences between historical and modern climates will be identified and the probable causes of changes will be investigated. Changes of the temperature climate of Svalbard will also be carefully studied by use of campaign measurements performed with automatic weather stations (AWS). These will be located at historical sites at Svalbard, where old meteorological stations previously have been operating. Based on the parallel measurements at the campaign sites and the currently running weather stations, statistical relationships will be established for various atmospheric circulation conditions. These relationships will be used to assess temperature conditions at the present weather stations in periods of the late 19th and early 20th century (i.e. before they were started), and to produce long (~100 years) monthly temperature series for the campaign sites.

WP5 Remote sensing and new technologies

WP-leader: Sandven (NERSC), co-leaders: L. Bobylev (NIERSC) and N. Mognard (CNES)

Objectives

The overall objective is to develop and utilize new observing system from satellites, automated ice buoys and underwater systems in order to improve data collection in the Arctic region. The focus of the WP will be to develop and validate methods for observing ice thickness, multiyear ice fraction, glacier mass balance, ocean primary production, river discharge, ocean freshwater and heat fluxes.

Research Plan

WP5.1 Sea ice cover, thickness and fluxes on large scale

***Partners**:* Sandven (NERSC), Haas (AWI), Nagurny (AARI), Ezraty (Ifremer), Heygster (IUP-UB), Toudal (DTU), Andersen (DMI), Løyning (NPI), Laxon (UCL), Alexandrov (NIERSC), Hughes (SAMS), Wilkinson (SAMS)

Tasks:

1) Improve and validate algorithms for retrieval of sea ice concentration and ice type classification (MY/FY/thin ice)
2) Develop and implement the algorithm to estimate sea ice thickness from ICESat and (from 2009) Cryosat data
3) Estimate ice drift and fluxes from EO data and validate the ice drift products for different areas and seasons
4) Provide time series of sea ice products for model validation and assimilation

State-of-the-art

The last decade has been observed as the warmest since the beginning of the 20th century, with the years 1998, 2002 and 2005 being the three warmest years. Concurrently the Arctic has been showing signs that significant changes are occurring, the declining of sea ice cover being one of them.

The most consistent, quantitative means to monitor the Arctic sea-ice cover is using satellite-borne passive microwave sensors. Basing on that data set a consensus in sea ice studying community that the total sea ice cover in the Arctic is decreasing at about −3% per decade has been established (Bjørgo *et al.*, 1997; Parkinson *et al.*, 1999; Comiso, 2002; Johannessen *et al.*, 2004; Belchansky *et al.*, 2005a; Belchansky *et al.*, 2005b). However, the estimates of changes that have occurred with multi-year (or perennial) ice in the Arctic are still debated.

The significance of the observed reductions in MY ice area in terms of the ice cover's mass balance could be quantitatively assessed if there were spatially- and temporally-coincident data on the ice thickness distribution. Sea ice thickness is a key diagnostic parameter; however, its variability is poorly known, due largely to spatial-temporal sampling deficiencies in data from submarines carrying upward-looking sonar. Satellite-borne laser altimeter data from NASA's ICESat satellite have shown the capability to map ice thickness (Kwok *et al.*, 2004). However, the reflection of the laser altimeter signal from different surface types needs to be investigated in order to establish robust retrieval algorithms. Significant advancements can be made using a multi-sensor approach, taking advantage of extensive new *in situ* data collections.

Long elastic-gravity waves (on the order of 1 km) in the sea-ice cover arise from the interaction with ocean swells. These elastic-gravity waves can propagate for hundreds to thousands of kilometers before dampening out. Based on a linear theory of free vibrations of the sea ice cover, the measured wavelength, wave period and direction are then related to thickness through a wave-energy dispersion relation. The ice thicknesses determined from different propagation directions are averaged to provide a basin-wide mean thickness estimate (Nagurnyi *et al.*, 1994).

Reduction in the MY ice coverage could be due to increased melt during summer and/or ice export through the Fram Strait. Persistent decreases in the summer ice coverage as observed would increase summer heating of the ocean by insolation and change the availability of thick multi-year ice outflow from the Arctic Ocean. As sea ice export through the Fram Strait represents a major source of surface fresh water for the Greenland-Iceland-Norwegian Seas, which are source regions of much of deep water in the world's oceans, variability in outflow is thus expected to have consequences in oceanic convective activity. Only the detailed description of MY ice movement and its transformations during winter season could give a full explanation of what has happened to MY ice coverage over the period of satellite observations.

***Methodology / work description*:**

The plan is to compare the existing passive- and active microwave sea ice algorithms (including NASA Team algorithm, the Bootstrap algorithm, the NORSEX algorithm and the IFREMER's technique), establishing retrieval accuracies and estimating reasons of discrepancies, in order to suggest improved algorithm to retrieve ice concentration and ice type from the large scale passive- (and possibly active-) microwave satellite data. The spatial and interannual variability of MY ice signatures will be evaluated and a new (spatial) model of different ice type signatures for the new algorithm will be suggested. The data to be used here are from SMMR, SSM/I and AMSR-E satellite sensors, QuikSCAT scatterometer data, data from subsequent satellite sensors and in situ data available from the partners. Finally time series of large-scale ice cover (ice concentration, ice type and ice area) from passive microwave satellite data since 1978 will be extended to include the period after 2005 and be made available for assimilation in climate models.

Both laser and radar altimeters can measure freeboard between the ocean surface and snow and ice surface, respectively. Ice thickness is retrieved from freeboard, assuming isostatic equilibrium and prescribed snow thickness and ice density (Laxon *et al.*, 2003; Kwok *et al.*, 2004). Since only a minor part of the floating ice is above the ocean surface, the errors in the freeboard determination are magnified significantly when calculating the ice thickness from freeboard. The ratio R between the ice freeboard and the ice thickness, which is determined by the ice, snow, and water densities, and the snow thickness, will be studied. Obtained estimates of R will be compared with those from publications. Measurements from field campaigns will be used for validation. Analysis of all these data will allow testing the validity of the hypothesis, that difference between laser-altimeter and radar-altimeter distances represents the snow thickness. Another hypothesis that needs to be tested is that the radar-altimeter signal is scattered from snow/ice interface. For this purpose radar altimeter-derived freeboards will be compared with those, measured in field. Based on conducted studies, the algorithm of ice thickness retrieval from radar-altimeter data will be developed.

The retrieval of ice thickness from ice vibration buoys will be performed, following up the work done by Nagurny (1994), showing thinning of the Arctic ice cover over the last two decades. The wave data can be a very useful method for validation of altimeter retrieved ice thickness. The ice vibration buoys will be deployed near the North Polar Drifting Station, collecting data continuously over several 2 years. Also use of EM-bird measurements will be performed from helicopter and icebreakers during the expeditions. Ice thickness from thin ice (<

about 0.5 m) can be retrieved from infrared satellite data (see WP5.2). In situ measurements of snow and ice properties including freeboard will be performed during field expeditions.

As to ice drift data, available ice-drift products (Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, produced by NSIDC and Gridded sea-ice drift vectors, produced by IFREMER) will be compared. Furthermore, ASAR global mode data will be obtained for ice drift and mapping of ice types and open water areas. Data on ice cover and ice drift will be used together with available ice thickness data to estimate total ice volume fluxes in different parts of the Arctic Ocean including the Fram Strait. Ice drift data will be used for assimilation in ice-ocean models and for validation of fluxes produced by the models.

WP5.2 Ice surface temperature and polynyas

Partners: Shalina (NIERSC), Smirnov (AARI), Feoktisov (NTs OMZ), Kloster (NERSC), Haas (AWI), Heygster (IUP-UB), Gerland (NPI), Nilsen (UNIS)

Tasks: Develop and apply state-of-art methodologies to describe the parameters of leads and polynyas, calculate ice surface temperatures, and estimate ice thickness from IR satellite sensors in order to provide better understanding of heat budget in the Arctic.

State-of-the-art

The presence of sea ice influences the temperature and circulation patterns of both the atmosphere and the oceans. Sea ice large area coverage, 5% of the ocean surface, makes the ice cover an essential parameter in the earth's energy balance. Ice surface temperature (IST) controls air–sea heat exchange and is an important parameter in large-scale modelling of the Arctic Ocean.

At present there are two IST products under development. The first one is based on MODIS data and produced at the MODIS Data Processing System (MODAPS) facility at GSFC (Riggs *et al.*, 1999; Hall *et al.*, 2004). For the retrieval of clear-sky IST, a split-window technique is used, where "split-window" refers to brightness–temperature differences in the 11–12 μm atmospheric window. This technique allows for the correction of atmospheric effects primarily due to water vapour. Another available IST product is based on the AMSR-E data and developed at the same NASA Goddard Space Flight Center (Comiso *et al.*, 2003). The applied algorithm uses the 6-GHz-channel AMSR data to account for ice temperature effects and generate ice temperature maps basing on Bootstrap sea ice concentrations. Both MODIS and AMSR products are preliminary and need further development and testing. Comparison of the two products shows large differences, up to 20 K, of the ice surface temperature in the central part of the Arctic in winter season. The algorithms need to be improved and acquisition of new field data from expeditions will be an important part of this work.

Methodology / work description:
It is planned to use MODIS Level 3 products MOD29E1D (based on Terra satellite observations) and MYD29E1D (based on Aqua satellite observations) that provide ice surface temperatures (ISTs) at daytime at 4km resolution and Level 1 MODIS data as well. Investigation of the MODIS products MOD29E1D and MYD29E1D shows that the data are highly contaminated by cloud pixels although they were produced using MODIS cloud mask product, so processing Level 1 MODIS data

will be necessary. The quality of ice surface temperature measurements greatly depend on the quality of cloud masking. Discrimination of clouds is particularly difficult in the polar regions because of the lack of contrast between temperatures and reflectance characteristics of certain cloud types and sea ice. It will be necessary to maximize accuracy of cloud detection elaborating efficient cloud tests. After successful cloud masking MODIS IR data will be used to produce monthly ice surface temperature maps. Heat fluxes in the Arctic will then be estimated.

Preliminary investigation of MODIS data has shown its high potential for the ice type discrimination. The description of IR characteristics of the types of ice in the marginal zone for different seasons will be suggested. MODIS data will be used together with SAR images to elaborate a methodology of sea ice classification in the marginal ice zone, revealing leads and polynyas, investigating their behaviour and estimating polynya heat fluxes in the Arctic Ocean. We will use the results of observations from field campaigns to validate the methodology.

Satellite IR data from Russian satellites will be provided by NTsOMZ in coordination with the field experiments. NTsOMZ will also analyse the Russian satellite data for retrieval ice temperature and heatfluxes.

WP5.3 Greenland Ice Sheet

Partners: Khvorostovsky (NIERSC), Johannessen (NERSC), Miles (BCCR), Bøggild (UNIS)

Task: To improve the estimates of net volume changes of Greenland ice mass by use of satellite altimeter data and in situ measurements.

State-of-the-Art

Determination of the Greenland Ice Sheet surface elevation and mass balance is thus important for determining its contribution to the sea-level rise and freshwater discharge (Thomas *et al.*, 2000; Rignot and Thomas, 2002). However, despite PARCA and other efforts, there is yet no consensus assessment of the overall mass balance of the ice sheet (Rignot and Thomas, 2002).

Satellite altimetry is one of the most precise methods that produces sufficient spatial coverage and density of the measurements needed to perform the study of the Greenland Ice Sheet (Zwally *et al.*, 1989; Davis *et al.*, 1998; Davis *et al.*, 2000). Satellite altimeter measurements of ice-sheet surface elevation variations allow us to determine directly the changes in ice volume including temporal variability and spatial distribution. SAR Interferometry gives the possibility to observe glacier flow and acceleration (Rignot and Kanagaratnam, 2006), and Automated Mass Balance Stations (AMS) will give in situ measurements of the mass balance (Bøggild *et al.*, 2003).

***Methodology / work description*:**

Altimeter data derived from ERS-1, ERS-2, ENVISAT and ICESat satellites will be acquired and processed. The methodology to be used to calculate elevation changes will be based on the crossover analysis using the differences in ice-mode altimeter ranges at crossing points of the satellite-orbit ground tracks. Elevation-change will be calculated for 0.5° lat. × 1.0° lon. cells to analyse its spatial distribution and temporal variability of spatial averages. Any possible inter-satellite biases will be thoroughly investigated using crossover differences between measurements from different satellites. The spatial distribution of elevation change will be investigated from its calculations for different drainage basins, elevation bands and latitude zones. The effect of topography, different climate and hydrological features, as well as surface properties, on the observed elevation change will be analysed. The temporal aspects, particularly the seasonal and interannual variability of elevation will be investigated, including their effect on elevation change-rate estimation.

Furthermore, all available SAR and passive microwave data will be analysed, focusing on SAR Interferometry to study glacier flows and acceleration along the margins of the Greenland Ice Sheet (Rignot and Kanagaratnam, 2006).

New methods have been developed for automated observation of meteorological and mass balance data for the Greenland Ice Sheet (Bøggild *et al.*, 2003). The new technology uses hydrostatic pressure sensors redesigned to measure ice melting. The sensors are installed to five times the depth of traditional stakes (with a proportional extension of lifetime of observation) in approximately the same time as installation of stakes. Moreover, the boundary layer climate is measured using an easy portable, ultra light and easy maintainable new tower concept where external power supply is eliminated using solar panels and satellite link provide access to data in near real time. The stations will transmit continuously meteorologhical and mass balance data.

The acquired ancillary *in situ* and modelled data will be used to interpret the obtained variability and change of Greenland Ice Sheet surface elevation in terms of physical characteristics (e.g., snow) that influence the altimeter-retrieved elevation and the ice sheet's response to external forcing factors. The Greenland ice-sheet elevation change-rate patterns will be analysed on intra-seasonal to decadal time scales, using both observations and model results. The recent trends in ice-sheet surface elevation derived from satellite altimetry will be interpreted in terms of accumulation and ablation and their linkages to air temperature and atmospheric circulation patterns. Furthermore, the results of mass-balance calculations obtained from general circulation model MPI ECHAM will be compared with satellite and ground-based data. Sensitivity of mass-balance from the different meteorological components, which are important on short-time scales, such as temperature, accumulation, cloudiness and precipitation will be considered. Thus, the nature of detected elevation change will be comprehensively investigated. Assessment of the entire ice sheet volume changes will show the contribution of Greenland Ice Sheet to freshwater discharge sea level rise.

WP5.4 Glaciers

Partners: Hagen (UiO), Kohler (NPI), Glazovski (IGRAS)

Tasks: To improve the estimates of net volume changes on Eurasian Arctic land-based ice masses by use of remote sensing data, in situ measurements and modeling.

State-of-the-art

Glaciers and ice caps are one of the key sources for the fresh water input to the oceans. Their mass budget directly affects sea level and upper ocean water masses as well as deep water formation and the thermohaline circulation.

Glaciers, ice caps, and ice sheets respond dynamically to climate changes over very different timescales depending on their size, shape, and temperature condition. The smaller glaciers are likely to respond quickly, with shape, flow, and front position changing over a few years or a few decades, while the Greenland ice sheet responds to climate changes on timescales of up to millennia. Parts of the Greenland ice sheet may still be responding to climate variations that occurred thousands of years ago. Especially the ice caps and glaciers in the wetter, more maritime parts of the Arctic region may be very vulnerable to rising temperature. In the next century, up to year 2100, it is believed that the glaciers and ice caps will contribute much more to global sea-level rise than the changes of the large ice sheets of Greenland and Antarctica (IPCC, 2001). Relative to the Greenland Ice Sheet, the smaller ice caps and glaciers can be susceptible to greater percentage changes of mass and area in response to changes of temperature and precipitation.

Recent events have demonstrated the potential for calving glaciers to undergo very rapid change. Calving glaciers that have retreated over large distances during the last hundred years, or even the last few decades, exist throughout the Arctic and subarctic. The volume lost by calving is not well known, and varies a lot across the Arctic. Calving must be taken into account in mass balance assessments.

***Methodology / work description*:**

The fresh water flux from glaciers in the European sector of the Arctic Ocean will be investigated by use of satellite remote sensing techniques used in combination with in situ measurements on a few selected glaciers. The only way to get spatial information is by remote sensing data, but these data must be validated by some ground-based measurements. The data will be combined with mass balance models to estimate the total volume changes. Data exists from some parts and some periods but need to be evaluated and processed in a systematic way.

Three different sets of remote sensing data will be used:
1. Surface properties and albedo data as input in mass balance models/melt models.
2. Elevation data. New laser altimeter data from ICESat will be used in combination with existing SAR, optical and radar altimeter data for estimation for volume change of glaciers in Svalbard and Russian Arctic. The hope is also to obtain elevation data from the planned CryoSat II within the project period. Ground-based GPS-profiles and airborne laser altimeter profiles will be used in selected areas to improve volume change estimates and calibrate the satellite data. In selected parts also old maps and aerial photos will be used to give long term volume change estimates.
3. Dynamic data. SAR-Interferograms to obtain velocity field estimates for input in calving flux calculations. Ground-based GPS-data will again be used in selected areas for validation.

Key target areas: Austfonna ice cap, Svalbard, Hansbreen, Kronebreen/Kongsvegen (Svalbard), Academy of Sciences Ice Cap (Severnaya Zemlya), Glacier No. 1 (Hall Island, Franz Josef Land)

WP5.5 Snow on land and on sea ice

Partners: N. Mognard (CNES/LEGOS), Heygster (IUP-UB), Shalina (NIERSC)

Tasks: Develop and validate methods for computing snow depth and snow water equivalent on land and sea ice, and estimate the spatio-temporal variability of the snowpack in the Arctic

State-of-the-art

Satellite passive microwave data have been continuously available since 1979; however the methodologies to compute snow depth still yield poor results on a global scale. A new methodology that uses a combination of passive microwave satellite brightness temperatures with air temperatures reanalyses and ground temperatures (Mognard and Josberger, 2002) provides a new means to estimate snow depth on a global basis (Grippa *et al.*, 2004; Grippa *et al.*, 2005; Boone *et al.*, 2006).

The new GRACE (Gravity Recovery and Climate Experiment) mission launched in March 2002 senses small-scale variations in Earth's gravitational pull from local changes in Earth's mass yielding new ways to estimate snow water equivalent anomalies over large Arctic river basins (Frappart *et al.*, 2006).

A methodology to compute snow depth deposited over sea ice has been developed over Antarctica using passive microwave satellite data (Markus and Cavalieri, 1998). However like the methodologies developed for snowpack over land, the snow crystal grain size variability has not been taken into account and might lead to a poor estimate of the snow depth over sea ice. Also no attempt has yet been tried to estimate Arctic sea ice snow depth on either first or multi-year sea ice.

***Methodology / work description*:**

The spatio-temporal variability of the terrestrial and sea ice snowpack plays an important role in the Arctic climate system through feedback processes with the atmospheric circulation, through its role in the Arctic freshwater budget and its influence on the thawing of permafrost. Time series of snowpack parameters (snow extent, snow depth, and snow water equivalent, dates of start of snowpack and snow melt) will be analyzed from the satellite passive microwave data available since 1979.

Snow on sea ice is determined routinely from the passive microwave sensor AMSR-E. However, the algorithm by Markus and Cavalieri (1998) calibrated with Antarctic observations for first-year ice has not been adapted to Arctic conditions. Determining the snow cover on multi-year ice from satellite observations appears difficult. First, more insight into the microphysical parameters which determine the emitted signal, their horizontal distribution and diurnal variation should be gained by collecting in situ data and using them in sea ice emission models. The new methodology based on the method developed by Mognard and Josberger (2002) over land will be applied to compute the snow depth over sea ice.

Time series of snowpack water equivalent anomalies will be analyzed from the GRACE satellite gravimetry data available since 2002.

WP5.6 Marine primary production

***Partners**:* Pozdniakov (NIERSC), Pettersson (NERSC)

Tasks: To use satellite ocean colour data to provide measurements of marine primary production in Arctic seas and validate retrieval algorithm for this region

State-of-the-art

The bio-optical algorithms (also called standard algorithms-SA) developed by NASA and ESA for the fulfilment of the above mission are solely appropriate for clear pelagic/off-coastal oceanic and marine areas (the so called case I waters), but they prove to be untenable for turbid waters in coastal zones (case II waters). At NIERSC an advanced algorithm is developed to retrieve water quality parameters in case II waters (Pozdnyakov *et al.*, 2004).

To overcome the problem of cloud screening, a special data interpolation procedure (DIP) has been developed at NERSC/NIERSC. Based upon the available statistical spaceborne *chl* data, this procedure provides for filling the desired information gaps.

A methodology for merging data from different sensors is not yet developed, although the first step – working out of the methodology for data binning, is already made.

A transition from ocean surface *chl* concentration data to quantification of phytoplankton primary productivity is another serious challenge since it requires information about *chl* vertical distributions. Several approaches have been suggested to overcome this difficulty, whose efficiency can only be assessed via ground truthing in each concrete case.

***Methodology / work description*:**

Based on the aforementioned new ocean colour data processing algorithms and techniques, and employing MERIS/MODIS data, generate monthly mean composites of phytoplankton *chl* for the Nordic Seas and the ice-free rim of the Arctic Ocean. Thus generated, *chl* maps will be largely free of cloud cover effects.

A pilot study will be conducted to extend the time series by merging MERIS and MODIS data. To reach this goal, MERIS and MODIS data on spectral remote sensing reflectance will be compared for some pre-selected areas (bins) given the time difference of overflight by both satellites is less than several hours. From such an analysis, a conclusion will be drawn as to the mergeability of data from the two ocean colour sensors.

Also, for some selected areas/bins ground-truthing will be achieved in order to choose a most appropriate approach for a transition from *chl* maps to mosaics of quantified phytoplankton primary production: statistically sound *chl* vertical profiles for the main three vegetation periods will be established under well-known conditions of atmospheric forcing and sun illumination. If successful, this research will provide the required data not in indirect terms of *chl* concentration, but directly in primary productivity values.

WP5.7 Freshwater runoff from Russian rivers

Partners: V. Ivanov (AARI), Kouraev (LEGOS), Bobylev (NIERSC)

Tasks: Use satellite radar altimetry combined with in situ measurements to estimate the runoff from large rivers into the Arctic Ocean, and estimate the spatio-temporal variability of the river runoff in the Arctic by analysis of historical data.

State-of-the-art

A general decline in the arctic hydrologic monitoring network in the Arctic area started in the mid 1980s (Shiklomanov *et al.*, 2002). In situ measurements of river discharge are therefore sparser than it was some decades ago. In this situation, use of microwave radar data can be a useful supplement to the in situ observations. It has been demonstrated that the TOPEX/Poseidon (T/P) radar altimeter could provide valuable information on water level variations of rivers, wetlands and floodplains with the precision of several tens of centimetres (Birkett, 1998; Maheu *et al.*, 2003). The applicability of satellite altimetry data for arctic rivers, where the presence of ice and snow perturbs the altimetric signal during a large portion of the year has recently been assessed and satellite radar altimeter data have been used in the Ob river basin to compute river runoff in the Arctic (Kouraev *et al.*, 2004). The spatio-temporal variability of the Arctic rivers plays an important role in the Arctic climate through its role in the Arctic freshwater budget and on the Arctic thermohaline circulation and as a tracer for the thawing of permafrost.

***Methodology/work description*:**
Time series of satellite radar altimeters continuously available since 1992 will be processed to derive estimates of Arctic runoff variability. The analyzed data sets will be provided for data archives and modelling to WP1. The runoff estimates from altimeter data will be validated against in situ measurements. For this purpose, new field investigations will be carried out in the estuaries and upstream in the major rivers Yenisei and Ob. The field measurements will include sea level data, hydrographical data, current measurements as well as direct measurements of river discharge.

WP5.8 Acoustic thermometry for ocean and sea ice observations

Partners: Sagen (NERSC), Skarsoulis (FORTH), Worcester (SCRIPPS)

Task: Develop and implement acoustic propagation methods for retrieval of ocean and sea ice parameters in the Arctic Ocean with focus on the Fram Strait

State of the art

Ocean acoustic tomography was introduced by Munk and Wunsch (1979; 1995) as a remote sensing technique for monitoring the ocean interior over large sea areas using low-frequency sound waves. Measuring acoustic observables, such as travel times, and their variations at fixed locations in the ocean, far away from a known source, and exploiting the knowledge about how the particular observables are affected by the distributions of the sound-speed (temperature, salinity) and current velocity, these distributions can be obtained by inversion. A large number of tomography experiments conducted in the world's oceans up to the present, e.g. Worcester and Spindel (2005), Skarsoulis *et al.* (2004) and Avsic *et al.* (2005) have demonstrated the feasibility of acoustically monitoring the ocean from the mesoscale to the basin scale.

The TAP (1994) and ACOUS (1998-1999) trans-Arctic experiments demonstrated the feasibility of acoustically measuring large-scale changes of temperature and heat content of the Arctic Ocean (Gavrilov and Mikhalevsky, 2002). These experiments revealed a significant basin-scale warming of the Arctic Intermediate

Water, in agreement with CTD data from the SCICEX 1995-2000 submarine expeditions. Furthermore, the 14-month ACOUS time series showed a remarkable correlation between the received acoustic energy and the integral path-average sea ice thickness changes (Gavrilov *et al.*, 2005). Propagation modelling predicts a direct relation between ice roughness and transmission loss (LePage and Schmidt, 1994; Duckworth *et al.*, 2001), whereas ice roughness and thickness are strongly correlated (Bourke and McLaren, 1992). This can be used as a basis for acoustically monitoring large-scale ice thickness changes, provided that the source level is known.

***Methodology / work description*:**

An acoustic tomography experiment will be conducted in the Fram strait from 2007 – 2009 to monitor the evolution of average temperatures across the West Spitsbergen current (WSC) and the East Greenland current (EGC). The tomography results will be assimilated into oceanographic models, which in turn will provide improved estimates of the heat, freshwater and ice fluxes through the strait. Underwater transmission and receiver arrays will be developed and deployed to measure acoustic travel-time measurements and transmission loss. These data will be analysed to retrieve data on hydrographical conditions (temperature and salinity) and ice parameters, especially ice thickness. The Fram Strait is a key area to test and validate the acoustical methods because there is an array of in situ current meter and ice thickness moorings in the regions. A longer term perspective is to implement acoustical transmitters and receivers as part of an ocean and sea ice monitoring system in the Arctic.

WP6: Assessment of Arctic climate change impact

Leader: Hanneson (SNF), co-leaders: H. Drange (NERSC), J. Haapala (FIMR)

Background

The Arctic has shown the most rapid rate of warming in the world and notable changes are already observed in the Arctic Ocean and subarctic regions (ACIA, 2005). Changes in the freshwater fluxes in the Arctic are expected to reduce the strength of the thermohaline circulation which could have a major impact not only on the Arctic and Subarctic regions, but also globally. Changes in Arctic climate and ecosystems will have significant impact on biomass production and fisheries. Some Arctic species are expected to be stressed by the reduction in the volume of Arctic water masses while in regions of reduced ice, primary production is expected to increase with corresponding increases in fish production (ACIA, 2005). Furthermore, as the Arctic Ocean becomes less ice covered, it can potentially become a new sink for CO_2. Less sea ice will also have significant impact on sea transportation and offshore industries. In particular the Northern Sea Route will be become more important because it provides access to the rich oil and gas fields in the Russian Arctic (ACIA, 2005). Climate change in the Arctic is already having a severe impact on indigenous people with a traditional lifestyle which is highly dependent on the environmental conditions (ACIA, 2005). Finally, extreme weather events and other climate change indicators (i.e. higher mean temperatures, reduction of glaciers) in different parts of Europe will be linked to the major climate indices (NAO, AO) in the Arctic.

This module will evaluate and synthesize the results on climate variability and change made in the other modules and assess their impacts in the Arctic. In this respect, IPY-CARE research will be continuing the ACIA work including attempts to reduce the uncertainties in the Arctic climate impacts and deepen our understanding of the processes underpinning the projected ecosystem changes in the Arctic Ocean and Subarctic regions. Improvements are expected because of enhanced use of existing data and new data collected under IPY-CARE as well as utilization of the next generation climate models. While the ACIA principally considered changes in the mean conditions over large regions, IPY-CARE will examine the changes to the interannual variability, extreme conditions and more regional characteristics. The emphasis will be on expected changes within the next 30 years.

Research on Arctic and boreal climate dynamics and change is relevant for resource exploitation, transportation, ecosystem preservation, fisheries and other aspects of environmental management in Arctic regions is of strategic importance for Europe. IPY-CARE will be important for the advancement of European excellence and competitiveness in Arctic science and technology including observational and forecasting systems. There is a strong need to improve our knowledge base and observation–prediction system for the following important societal issues:

1. ***Ecosystems and fisheries:*** Improved understanding and preservation of the Arctic ecosystem (Beaugrand *et al.*, 2002) is of high priority in Europe. Climate change can affect fish population structure with impact on fisheries in the Nordic and Barents Seas, which are among the most important in the world.
2. ***Exploitation of hydrocarbon resources:*** Europe has significant interest in the exploitation of oil and gas, mineral and other resources in high latitudes offering exciting opportunities for European energy and transport industry.
3. ***Sea transportation:*** European shipping industry has started to prepare for increased use of the Northern Sea Route (NSR)(Ragner, 2001), which is a much shorter sailing route between Europe, the Far East and the west coast of North America. It is also the main export route for oil, gas, minerals, timber, etc from Russia to Europe.
4. ***Pollution transport:*** Europe is responsible for much of the pollution going into the Arctic regions**.** Improved understanding of transport of pollutants including radionuclides is needed as well as potential spreading of radio-nuclides from the Russian Arctic regions (Macdonald *et al.*, 2003).
5. ***Arctic Ocean as sink for CO_2:*** There is a need to assess the role of the Arctic Ocean with decreasing ice cover as a new sink area for CO_2 from the atmosphere (Anderson and Kaltin, 2001).
6. ***Socio-economic and human impact of climate change*:** There is a need to assess the requirements for mitigation strategies for consequences of extremities of weather and climate, such as floods, droughts, etc.

Research plan

WP6.1 Impact on Barents Sea ecosystems

Partners: Loeng (IMR), Titov (PINRO)

Task: To quantify the changes in the marine ecosystem, in particular in fishery resources, biomass production and biodiversity.

Background

This impact activity contributes to the study of the impacts of changing conditions in the Arctic Ocean and climate on the marine ecosystem. For certain processes, the ocean responds more or less passively to atmospheric changes. In other cases, feedback mechanisms link ocean and atmosphere, and it is clear that the ocean plays a very important role in climate change and variability. The Arctic Climate Impact Assessment (ACIA, 2005), when assessing climate impact on the Arctic, pointed out several gaps of knowledge that need to be addressed during the forthcoming years. Filling these gaps can only be achieved via monitoring and research, some requiring long-term effort. For certain processes, the ocean responds more or less passively to atmospheric changes. In other cases, feedback mechanisms link ocean and the atmosphere, and it is clear that the ocean plays a very important role in climate change and variability. Large, long-lived Arctic species tend to have very stable populations, so even dramatic changes in juvenile survivorship may not be easily detected for a considerable period of time. At the other end of the size range of organisms, natural variation in population size of phytoplankton is generally large and can mask detection of longer-term trends in abundance. Thus, long-term data series are essential to monitor climate-induced change in Arctic marine ecosystems. IPY-CARE results will be used to determine ecosystem change and change in biomass as food sources for fish species.

Methodology / Work description

IPY-CARE will focus on studies in the Barents Sea where the commercially most important fish species in the Arctic are found. The studies will focus on the climate impact on the Barents Sea ecosystem. This research will quantify the impact of climate variability on the structure and function of the Barents Sea marine ecosystem in order to predict the ecosystem response to possible future climate change and its possible economic impact (human impact activity. We will use data from past and ongoing projects as well as undertake new research to address how the climate forcing of the physical oceanography of the Barents Sea and the impacts on the ecosystem. This will be based mostly upon a retrospective analysis but modelling results from WP1 and will in addition use info from WP2.

WP6.2 Impact on fisheries

Partners: Hanneson (SNF), Loeng (IMR), Titov (PINRO), Mathishov (MMBI)

Task: Estimate the likely changes in revenues from fishing, costs of fishing and fish processing, and export earnings.

Background

Changes in ocean temperature, sea ice and salinity will affect the habitat and migrations of fish stocks. The habitat of some stocks is likely to be displaced in a northward direction as a result of a warmer climate, and migratory fish stocks are likely to occur further north. In addition the productivity of fish stocks may change, in a positive or negative direction, depending on how changes in ocean climate affect the abundance of prey and predator species of each particular stock, or age groups within a stock.

The economic effects of these changes will be of two major kinds:

(i) Effects of changed productivity and occurrence of stocks on fish catches.

Higher (lower) productivity of fish stocks will increase (decrease) fish catches, provided the stocks are managed efficiently by a rule relating fish catches to stock abundance. This will directly affect the value of fish production, although not necessarily proportionately, because fish prices may depend on the volume of fish catches from the stock(s) affected. Changes in catches of fish and their geographic location will necessitate changes in the capacity of fishing fleets and fish processing facilities and the location of such activities, especially fish processing facilities, as boats are geographically mobile while fish processing plants are not. Changes in fish catches and the localities where they are landed will have repercussions for where people live and work, causing unemployment in certain places while increasing employment in others.

(ii) Effects of changed fish migrations and displacements of fish habitats on sharing agreements for fish stocks. Almost all fish stocks utilized by the Norwegian fishing fleets are shared with other nations. The Northeast Arctic cod and the Barents Sea capelin are shared with Russia according to rules established when the exclusive economic zones were established in 1977. Stocks in the North Sea are shared with the European Union, likewise on the basis of rules established in the late 1970s. The Norwegian spring spawning herring and some other stocks in the Northeast Atlantic are shared with Iceland, the Faeroe Islands, and a number of other nations. The Norwegian-EU agreement is explicitly based on the so-called zonal attachment, i.e., how much of each fish stock is found in the exclusive economic zone of EU and Norway, respectively. Even if the other agreements are not based on the zonal attachment, the location and migrations of fish stocks have an obvious bearing on the sharing of these stocks, since this decides what each party could do on its own in the absence of an agreement and so defines a bottom line below which a country will not be interested in cooperation. Therefore, changes in fish stock habitats and migrations may upset existing agreements, as they might make it more attractive for one particular country to renege on existing agreements and operate independently. For example, if the Northeast Arctic cod stock would migrate into the Russian economic zone to a much greater extent than it does now, Russia might find it attractive to abandon the present 50-50 sharing agreement and decide on her own how much to fish in her own zone.

Methodology / Work description

The work under this package will be based on predictions by fisheries biologists with regard to the points under (i) and (ii) above:

(i) Based on quantitative predictions/scenarios, estimate the likely changes in revenues from fishing, costs of fishing and fish processing, and export earnings. Estimate likely changes in the needed capacity of fishing fleets and processing facilities and the consequent changes in employment and population in counties and municipalities in fishery-dependent areas.

(ii) Based on predictions/scenarios regarding fish migrations and distribution of habitats, investigate whether existing fish sharing agreements are likely to be undermined by these changes by making it attractive for some members of an agreement to break it. Furthermore, investigate how existing agreements could be revised in order to accommodate changes in fish habitat and migrations to avoid the overexploitation and possibly extinction of fish stocks that otherwise would occur as a result of breakdown of agreements. The methodology applied in this research will be game theory, both cooperative and non-cooperative.

WP6.3 Impact on offshoire oil and gas industry

Partners: Hanneson (SNF), Danilov (AARI)

Task: estimate the likely deposits of oil and gas which will become accessible in the Arctic as a consequence of climate change, estimate the likely costs of exploiting the resources and make scenarios of oil and gas prices and estimate conditions under which exploitation will become profitable

Background

The reduction in sea ice cover and frequency of icebergs will open up areas for oil and gas exploration which now are inaccessible. This is likely to increase the exploitable oil and gas reserves on the Barents Sea continental shelf. This question has an obvious relevance for long term economic planning in Norway and Russia, whose economic zones cover the Barents Sea continental shelf. A larger resource base will extend the period for which oil and gas extraction will last and probably increase the volume extracted at any point in time as well. This will strengthen the case for building up a costly and elaborate infrastructure to process and transport oil and gas from this remote region, especially with respect to natural gas which requires either costly liquefaction terminals or pipelines over difficult terrain and long distances.

Despite these changes, the Barents Sea is still likely to remain a marginal area, demanding intricate and expensive technical solutions. Extreme weather conditions, especially icing, are likely to prevail and possibly to be intensified (increased frequency of storms at freezing temperatures), and variations around a warming trend may produce temporary advances in ice cover and occurrences of icebergs. This may make it necessary to shut down production for certain periods or to find technological solutions that could deal with such occurrences. All of this makes the Barents Sea marginal in terms of extraction costs for oil and gas, and so any increase in the resource base must be carefully assessed against the high extraction costs. Because of this, the future development of oil and gas prices is likely to be critical for the economic viability of this area, making it one of the most risky ones in the world in economic terms.

Methodology / Work description

Based on predictions of changes in ice cover and occurrences of icebergs, and on existing knowledge about the geology of the continental shelf in the Barents Sea, estimate the likely deposits of oil and gas in this area that will become accessible.

Based on existing technology applied in the Barents Sea region, estimate the likely costs of extraction of oil and gas for these additional resource deposits.

Based on likely scenarios for the future price of oil and gas, determine whether and under what conditions these new deposits will be worthwhile to exploit. These scenarios will involve forecasts of economic growth, substitution of other types of energy sources for oil and gas, the effects of CO_2 removal technologies, and supplies from alternative sources and their position in the market. For the European gas market it will be particularly important to apply strategic analysis (industrial organization analysis) to future price scenarios, as this is a market with only a few major players (Norway, Russia, Algeria) where decisions by a single player have a major impact on the results realized by others through price effects. Based on the above, what is the implication for the economic viability of costly infrastructures for natural gas exports, both liquefaction plants and pipelines?

WP6.4 Impact on the thermohaline circulation

Partners: Fichefet (UCL-ASTR), Haapala (FIMR), Shapiro (UoP), Wadhams (UCAM-DAM)

Task: To assess effect of the changes in a surface heat and fresh water fluxes on the Atlantic thermohaline circulation and meridional overturning.

Background

Theoretical studies and numerical experiment have shows that the strength of thermohaline circulation (THC) and the Atlantic meridional circulation (MOC) depends on the heat and fresh water fluxes at the high latitudes. However, the climate change in the Arctic and the changes in the Atlantic thermohaline circulation can't regard as a one-way causal relationship, since the changes of the THC are expected to lead changes in the Arctic climate. Present understanding is that the climate warming in the high latitudes will weaken THC mostly due to the changes of the surface heat fluxes (Gregory et.al, 2005). Weakening of the THC will result about 30 % weakening of the Atlantic MOC, but it will not results cooling of the North Europe or even compensate general warming trend. However, the strength of the Atlantic MOC in future is still very open question. This assessment rely upon the new scientific results and since the Atlantic MOC is one of the key research topics of the European oceanographic research community, much advance in an understanding of the relationship between the MOC and climate change in the Arctic is expected during the following years.

Methodology / Work description

Based on tailored numerical experiments with a hierachy of climate models, and on existing knowledge the assessment will investigate on the following questions

1) How much strength and response of the MOC depends on the used models, physical parameterizations and resolution?

2) How much surface currents and oceanic heat transport change due to the changes of the THC?

3) What is the effect of increases melting rate the Greenland ice sheet on the THC?

4) How much the MOC should weaken to cause cooling of the Europe?

5) Could climate warming in the Arctic trigger a complete shutdown of the MOC?

(The other impact studies are not yet defined)

Organisation and management

Overall management: The project coordinator together with the administrative and financial manager will be responsible for the overall coordination and management according to a project management plan. The coordinator is responsible for coordination between the WP leaders. The co-ordinator will be supported by the deputy co-ordinator.

Prof. Ola M. Johannessen, Director at NERSC, will be the project co-ordinator. He has many years experience as scientist (Johannessen *et al.*, 1999b; Alekseev *et al.*, 2001; Bengtsson *et al.*, 2004; Johannessen *et al.*, 2004; Kuzmina *et al.*, 2005) and leader of Arctic projects and oceanographic/sea ice experiments with international participation, such as NORSEX (Johannessen *et al.*, 1983), MIZEX (Johannessen, 1987) and SIZEX (Sandven and Johannessen, 1990). He has been the Coordinator of several EU projects including AMOC (Johannessen *et al.*, 1999a) and Arctic Ice Cover Experiment (AICSEX) (Johannessen *et al.*, 2004). Stein Sandven, research director at NERSC, is the deputy coordinator of IPY-CARE. He has 20 years experience in Arctic research and coordination of international projects.

Steering committee: A project steering committee has been established, as shown in front page to make decisions on higher level scientific and management issues. The steering committee will have meetings every 6 months.

Prof. Jörn Thiede, Director of AWI, is the Chairman of the Steering Committee. He has extensive experience as scientist (Thiede and Bauch, 1999; Thiede *et al.*, 2001a; Thiede *et al.*, 2001b; Thiede *et al.*, 2002) in leading large international Arctic research projects and presently directing one of the largest polar institutes in the world. Prof. Lennart Bengtsson (Schneider *et al.*, 2003; Bengtsson *et al.*, 2004; Johannessen *et al.*, 2004), one of the leaders in climate modelling in the world, is the co-chairman of the steering committee.

WP Leaders: Each WP has a Leader responsible for co-ordination of the work assigned to the WP, supported by 1 – 2 co-leaders. The Leader will report to the project coordinator and the steering committee. The leaders and co-leaders for the scientific WPs are the following:

WP1 Leader: L. Bengtsson (MPIfMet), co-leaders: U. Schauer (AWI) and I. Frolov (SRC AARI)
WP2 Leader: S. Falk-Petersen (NPI), co-leaders: D. Piepenburg (IPOE/ASM) & L. Anderson (UGOT)
WP3 Leader: J.-C. Gascard (UPMC/LODYC), co-leaders: B. Rudels (FIMR) and P. Haugan (BCCR)
WP4 Leader: R. Spielhagen (ASM/GEOMAR), co-leader: N. Koç (NPI)
WP5 Leader: S. Sandven (NERSC), co-leaders: L. Bobylev (NIERSC) and N. Mognard (CNES)
WP6 Leader: R. Hannesson (SNF), co-leaders: H. Drange (NERSC) and J. Haapala (FIMR)

Expert groups: A group leader will be responsible for planning, coordinating, monitoring and reporting of all the work within each expert group and edit the contribution from each group to the science plan and implementation plan.

Communication Policy: The communication policy aims to keep all the partners fully informed about the project status, the planning and all other issues which are important to the partners in order to obtain maximum transparency for all involved and to increase synergy of the cooperation. The communication strategy also aims to effectively communicate with parties outside the consortium, such as with EU and other European projects, potential users of the technology, international climate programmes and with policy bodies and decision makers.

Dissemination and exploitation: A dissemination plan will be prepared for use and exploitation of results from the project. The plan will include publications, presentations and other promotion activities. Web-based dissemination of information within as well beyond the consortium will be implemented. Any publications or presentations will take into account intellectual and industrial property aspects and will be in conformity with the dissemination policy. The exploitation strategy of IPY-CARE will aim to implement new observing systems for the high latitudes as an IPY component of operational monitoring and forecasting of climate.

IPR issues: IPR issues will in general be handled by the Steering Group. Guidelines are proposed for the Consortium to avoid conflicts and secure the interest of the partners, as indicated in the following paragraphs.

Ownership of data: All data delivered to the partnership is in principle the property of the partner(s) providing the data. For some data with restricted access, for example satellite SAR data, it is planned to order jointly data from the consortium for the IPY-CARE studies, in which case the data is owned by the whole consortium. This implies that the members have equal rights to use and distribute data under conditions agreed with the data supplier. Data are in principle open for free use for non-commercial purposes. Restrictions to use and distribution may apply to some types of data, but the general rule should be that all data are made freely available for research purposes as soon as possible. Research data that are not quality controlled may also have restricted distribution. The data are encouraged to be used in research and development work including validation that is beneficial for the IPY-CARE programme.

Methods and algorithms for retrieval of geophysical and biological data from raw data or instrument data: All methods and algorithms provided by partners are in principle owned by the developer following normal copyright rules. Exchange of methods/algorithms between the partners is encouraged as part of capacity building and standardization of the data analysis.

Software delivered by system developers and other partners to be used by consortium members and/or end users will follow normal software sales and licensing rules between providers and customer.

Coupled models: Models, assimilation methods and corresponding software code are owned by the partner(s) who have developed the model system.

Plan for use and dissemination of knowledge

The partners consider several of the new methodologies proposed for observing the Arctic marine and cryospheric environment to have a good potential to become operational monitoring systems that will be important for climate monitoring in the Arctic. On the modelling side, the partners expect that IPY-CARE can support the implementation of European model systems (ocean models, sea ice models, ecosystem models, etc.) in the Arctic. The development of improved observation and modelling techniques from a European IPY programme will enable the partners to increase their competence and ability to generate new and innovative components of global observing systems. This will strengthen the role of European research and industry in the implementation of new observation systems as well as modelling systems for the Arctic.

In the exploitation of the results, a wide range of potential users and stakeholders will be contacted, showing the importance of integrated measurements from satellite, aircraft, ships and automatic buoys for measurement of Arctic climate and ecosystem parameters. The presence of sea ice in the Arctic Ocean has important impact on transport, industries, economies and human settlements in Northern Europe and polar regions. This will be particularly addressed in Module 6: Impact of Arctic Climate Change.

The IPY-CARE results is planned to be disseminated towards different target groups:

1) Dissemination towards practical operators in Arctic regions

- Shipping companies and sea transportation administration
- Icebreaker captains and ice pilots of ships
- Oil companies and offshore construction
- Fishing vessels and coast guards
- National ice services
- Tourism and leisure activities

2) Dissemination towards international organisations and programmes for the Arctic and Antarctic

- WMO/IOC's Joint Technical Commission for Oceanography and Meteorology (JCOMM) is focusing more on polar regions and has taken initiatives to push the development of observation of better systems in the polar regions.
- Arctic Monitoring and Assessment Programme (AMAP) and Conservation of Arctic Flora and Fauna (CAFF) under Arctic Council
- Climate research and monitoring programmes (i.e. CliC and institutions working with CliC projects)
- Arctic Marine Shipping Assessment 2005 – 2008 under PAME of the Arctic Council.
- GOOS / CGOS / EUROGOOS working to develop operational monitoring and forecasting systems for the Arctic

3) Dissemination towards other stakeholders such as

- Politicians (EU and national level) with commitments to climate protocols, etc.
- regional and national authorities with responsibilities for infrastructure and services in sea ice areas
- Insurance industry
- IMO

4) Dissemination to the general public via Internet, newspapers and TV

Outreach to the general public will be achieved through dedicated popular-science dissemination through journals, newspapers, television and internet-based dissemination.

5) Publications in scientific & technical journals and presentation of results at conferences related to polar and climate topics

Scientific results will be targeted to high-profile international journals with a high "impact factor", e.g., *Nature*, *Science*, *Climate Dynamics*, *Journal of Climate*, *Tellus*, etc. Scientific results, including historic and new datasets will also be disseminated to the international programmes, monitoring, assessment and policy-making organizations.

6) Education and training.

Preparation of educational material for use in maritime colleges and universities, plan and implement international exchange programmes and training for scientists and students.

7) Technology transfer

Technology development and scientific service will be transferred to and from SMEs.

Other issues

Ethical issues

IPY-CARE is not assosiated with

human, organ, cell or genetic research
animal experiments
personal data and privacy

There are no other ethical impacts of the project results. As normal in research work, all financial dealing of the proposed work is open for review. All the participants involved are under national auditing systems and under the financial overview of the Commission for projects funded by EU FP6, consortium agreement will be pursued after the project commence, to define mutual obligations between partners. This will also concern where necessary, IPR issues, non-disclosure, registered designs, copyright and trademarks.

Gender issue

All participant institutions are equal opportunity employers, and will follow up "the gender mainstreaming strategy by which each policy areas, including that of research, must contribute to promoting gender equality" as the European Commission has adopted.
In case the project has to advertise for new employees strong attempts will be made by all the partners to find well-qualified female candidates. This will follow up the gender policy the involved countries try to follow up.

"The Commission recognizes a threefold relationship between women and research, and has articulated its action around the following:

1. Women's participation in research must be encouraged both as scientists/technologists and within the evaluation, consultation and implementation processes,
2. Research must address women's needs, as much as men's needs,
3. Research must be carried out to contribute to an enhanced understanding of gender issues" (From the "Guide for proposers").

When we follow up these three actions in the project we will keep in mind that "Ensuring gender equality means giving equal consideration to the life patterns, needs, interests of both women and men". Focus will be on action 1, while the others are not relevant for IPY-CARE.

During the planning and implementation of the IPY-CARE project activities specific actions will be taken to ensure that female scientists will be involved at all levels (steering committee, WP leaders and task leaders) within the project. Furthermore, female scientists and Ph. D. students will be fronted in the promotion of the project and the project results towards both scientific communities and for example towards the other important groups as children and undergraduate students. This last activity is very important for changing the low representation of women within polar science, but also to raise the general interest of science among young people.

Field programmes

Use of research ships and ice-going vessels

The field programmes in the high Arctic will be performed with icebreakers *RV Polarstern* (Germany), *Oden* (Sweden) and *A. Fedorov* (Russia). These will mainly be summer expeditions in 2007 – 2008 and will be co-funded by the EU DAMOCLES integrated project. In addition, the Russian North Polar Drifting Station will operate throughout the year in the central Arctic.

In the Nordic Seas including the marginal ice zones there will be a number of expeditions in 2007 – 2008 (Fig. 6). The freshwater discharge from Greenland ice sheet will be studied in two summer cruises with *RV Håkon Mosby* along the Greenland coast and regular three-weekly passages by the container vessel *Nuka Arctika* between Greenland and Denmark, also providing mean heat and mass transports at the southern boundary of the Nordic Seas. The freshwater discharge will be complemented by two automated mass balance stations deployed by helicopter on east Greenland glaciers. Dedicated IPY- cruises will be carried out by IMR-ships (Bergen) and PINRO-ships (Murmansk) to study the open ocean freshwater distribution. The Polish RV Oceania will conduct summer expeditions to the Greenland Sea and Fram Strait for hydrographical surveys. In addition, freshwater discharge from Russian rivers will be studied by modern satellite altimeter techniques, calibrated with in situ observations. In the Fram Strait acoustic tomography moorings will be deployed by RV Lance in order to estimate freshwater fluxes and sea ice thickness (deployment in the EU/RCN project DAMOCLES).

On Svalbard, the following three field experiments will be carried out: glacier mass balance studies, sediment coring in fjords and lakes, and mesocosm experiments at the Marine Laboratory in Ny-Ålesund. From Whalers Bay north of Svalbard towards the North Pole, an air- ice-ocean transect and physical and biogeochemical process studies will be carried out in winter and summer by ice-going *KV Svalbard*, including use of helicopter, drones and hovercraft. The latter activity will be complemented by ice thickness observations by the electromagnetic method (EM-bird from helicopter, hovercraft and ice-going vessel), ice vibration buoys and remote sensing validation work from icebreaker *A. Fedorov* and the Russian North Polar Drifting Station.

The essentially unknown Atlantic inflow to the Arctic Ocean through the pathways in the Northern Barents Sea will be recorded by sediment coring for the past 10000 years. Direct current and hydrographic measurements in these pathways will be obtained in collaboration with Russian field campaigns by *A. Fedorov*.

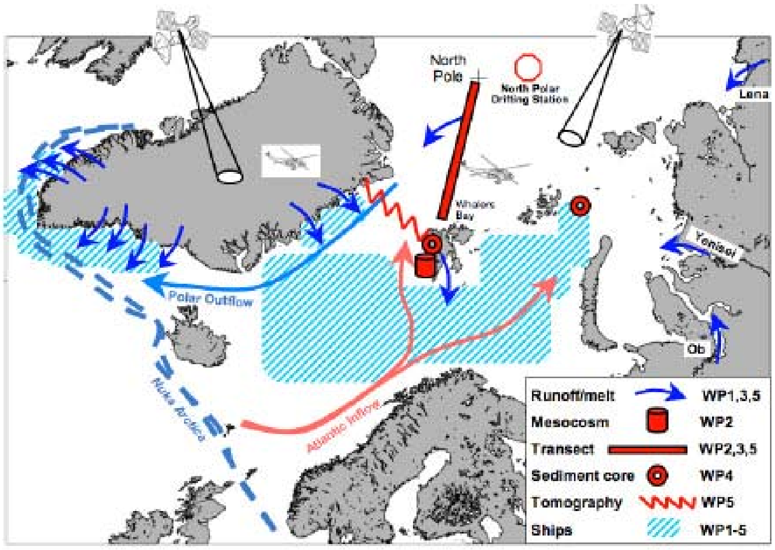


Figure 6. Planned field activities in the European sector of the Arctic including the Nordic Seas.

Use of hovercraft as an innovative research platform

The application of hovercraft as an integrated platform for research in the Arctic is an innovative alternative compared to traditional platforms such as icebreakers, helicopters and airplanes. This was tested out by Y. Kristofferesen and O. M. Johannessen in May 1992 where a hovercraft was used in the fjords of Svalbard and in ice-infested waters north of Svalbard with excellent results (see report by Kristoffersen (1994)).

The plan is to buy the 12 m long Griffon hovercraft (model 2000 TD), specially designed for Arctic operations (Fig. 7). It will be equipped with atmospheric and ocean instruments, radiometers for remote sensing validation, biological sampling gear and quarters for personnel. This hovercraft will be operated from Svalbard, ice-going Norwegian coastguard vessel *KV Svalbard*, and *RV Polarstern* of AWI. It will carry out mesoscale ocean experiments in ice-infested waters of Barents Sea, Svalbard region and Eurasian Arctic, complementing the larger scale surveys which are traditionally carried out by icebreakers and fog-limited helicopters. In addition it will be an important platform for air-sea-ice process studies in leads and polynyas. Based on the experience from the operations in 2007 – 2008, the hovercraft will be evaluated for future work as general platform for Arctic field studies in sea ice areas.

Figure 7. Photograph of a Griffon 200TD

Specifications for the Griffon 2000TD:
Length 12.7 meters
Beam (hovering): 6.1 meters
Height (hovering): 3.93 meters
Passengers (excluding crew): 20-25
Minimum crew: 1
Maximum payload: 2.2 tonnes
Maximal endurance: 10 hours
Normal consumption: 45 litres/hr
Speed at full payload: 35 knots
Engine type: 1 Deutz (diesel)
Power per engine: 265 kW/355 HP
App. obstacle clearance: 0.73

hovercraft operating in sea ice

Implementation Plan

The implementation plan for IPY-CARE is under development and will be completed during 2006. A workshop on IPY-CARE implementation is planned to be held at the Nansen Environmental and remote Sensing Center in in November 2006.

References

ACIA (2005) *Arctic Climate Impact Assessment*, Cambridge University Press, 1042 p.

Alekseev, G. V., O. M. Johannessen, A. A. Korablev, V. V. Ivanov and D. V. Kovalevsky (2001) Interannual variability in water masses in the Greenland Sea and adjacent areas, *Polar Research*, **20**: 207-210.

Ambrose Jr., W. G. and P. E. Renaud (1997) Does a pulsed food supply to the benthos affect polychaete recruitment patterns in the Northeast Water Polynya? *Journal of Marine Systems*, **10**: 483-495.

Anderson, L. G. and S. Kaltin (2001) Carbon fluxes in the Arctic Ocean - potential impact by climate change, *Polar Research*, **20**: 225-232.

Anderson, L. G., K. Olsson and M. Chierichi (1998) A carbon budget for the Arctic Ocean, *Global Biochemical Cycles*, **12**(3): 455-465.

Avsic, T., U. Send and E. K. Skarsoulis (2005) Six years of tomography observation in the central Labrador Sea, *Conf. Underwater Acoustic Measurements*, Heraklion.

Bauch, H. A. and Y. I. Polyakova (2003) Diatom-inferred salinity records from the Arctic Siberian margin: implicarions for fluvial runoff patterns during the Holocene, *Paleoceanography*, **18**(2): 501-510.

Beaugrand, G., P. C. Reid, F. Ibanez, J. A. Lindley and M. Edwards (2002) Reorganization of North Atlanric marine copepod biodiversity and climate, *Science*, **296**: 1692-1694.

Belchansky, G. I., D. C. Douglas, V. A. Eremeev and N. G. Platonov (2005a) Variations in the Arctic's multiyear sea ice cover: A neural network analysis of SMMR-SSM/I data, 1979-2004, *Geophysical Research Letters*, **32**(L09605): doi:10.1029/2005GL022395.

Belchansky, G. I., D. C. Douglas and N. G. Platonov (2005b) Spatial and temporal variations in the age structure of Arctic sea ice, *Geophysical Research Letters*, **32**(L18504): doi:10.1029/2005GL023976.

Bellerby, R. G. J., A. Olsen, T. Furevik and L. A. Anderson (2005) Response of the surface ocean CO_2 system in the Nordic Seas and North Atlantic to climate change. *Climate Variability in the Nordic Seas*, H. Drange, T. M. Dokken, T. Furevik, R. Gerdes and W. Berger, AGU, **158:** 189-198.

Bengtsson, L. (2006) A Proposal for a Dynamical Climate Reanalysis, *Bulletin of the American Meteorological Society*, **accepted**.

Bengtsson, L., K. I. Hodges and E. Roeckner (2006) Storm tracks and climate change, *Journal of Climate*, **accepted**.

Bengtsson, L., V. A. Semenov and O. M. Johannessen (2004) The early century warming in the Arctic - A possible mechanism, *Journal of Climate*, **17**(20): 4045-4057.

Bianchi, G. G. and I. N. McCave (1999) Holocene periodicity in North Atlantic climate and deep-ocean south of Iceland, *Nature*, **397**: 515-517.

Birkett, C. (1998) The contribution of TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands, *Water Resources Research*, **34**: 1223-1239.

Birks, C. J. A. and N. Koc (2002) A high-resolution diatom record of late-Quaternary sea-surface temperatures and oceanographic conditions from the eastern Norwegian Sea, *Boreas*, **31**: 323-344.

Bjørgo, E., O. M. Johannessen and M. W. Miles (1997) Analysis of merged SMMR-SSMI time series of Arctic and Antarctic sea ice parameters 1978-1995, *Geophysical Research Letters*, **24**(4): 413-416.

Bobylev, L. P., K. Y. Kondratyev and O. M. Johannessen, Eds. (2003) *Arctic Environment Variability in the Context of Global Change*, Springer - Praxis Publishing, 470 p.

Boone, A., N. Mognard, B. Decharme, H. Douville, M. Grippa and K. Kerrigan (2006) The impact of simulated soil temperatures on the estimation of snow depth over Siberia from SSM/I compared to a multi-model climatology, *Remote Sensing of Environment*, **submitted**.

Bourke, R. H. and A. S. McLaren (1992) Contour mapping of Arctic Basin ice draft and roughness parameters, *Journal of Geophysical Research*, **97**(C11): 17715-17728.

Bryden, H. L., H. R. Longworth and S. A. Cunningham (2005) Slowing of the Atlantic meridional overturning circulation at 25°N, *Nature*, **438**(7068): 655.

Bøggild, C. E., C. Mayer, O. B. Olsen, P. Jørgensen, J. Heinsdorf and B. Petersen (2003) Modern mass balance observations at the Greenland ice sheet margin, *14th International Symposium and workshop on Northern Research Basins*, Kangerlussuaq, Greenland.

Carroll, M. K. and J. Carroll (2003) The Arctic Seas. *Biogeochemistry of Marine Systems*, K. Black and G. Shimmield, Sheffield, UK, Blackwell.

CMIP2 (2003). Coupled Model Intercomparison Project (CMIP2).

Collins, M., M. Botzet, A. Carril, H. Drange, A. Jouzeau, M. Latif, O. H. Otterå, H. Pohlmann, A. Sorteberg, R. T. Sutton and L. Terray (2006) Interannual to decadal climate predictability: A multi-perfect-model-ensemble study, *Journal of Climate*, **accepted**.

Comiso, J. C. (2002) A rapidly declining perennial sea ice cover in the Arctic, *Geophysical Research Letters*, **29**(20): 1956, doi:1910.1029/2002GL015650.

Comiso, J. C., D. J. Cavalieri and T. Markus (2003) Sea ice concentration, ice temperature, and snow depth using AMSR-E data, *IEEE Transactions on Geoscience and Remote Sensing*, **41**(2): 243-252.

Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, S. C. B. Raper and K. S. Yap (2001) Projections of future climate change. *Climate*

Change 2001: The scientific basis, J. T. Houghton, D. Yihui and M. Noguer, Cambridge University Press.

Curry, R., B. Dickson and I. Yashayaev (2003) A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, **426**: 826-829.

Curry, R. and C. Mauritzen (2005) Dilution of the northern North Atlantic Ocean in recent decades, *Science*, **308**: 1772-1774.

Davis, C. H., C. A. Kluever and B. J. Haines (1998) Elevation change of the southern Greenland ice sheet, *Science*, **279**: 2086-2088.

Davis, C. H., C. A. Kluever, B. J. Haines, C. Perez and T. Yoon (2000) Improved elevation-change measurement of the southern Greenland ice Shet from satellite radar altimetry, *IEEE Transactions on Geoscience and Remote Sensing*, **38**(3): 1367-1378.

Delille, B., J. Harlay, I. Zondervan, S. Jacquet, L. Chou, R. Wollast, R. G. J. Bellerby, M. Frankignoulle, A. V. Borges, U. Riebesell and J.-P. Gattuso (2005) Response of primary production and calcification to changes of pCO_2 during experimental blooms of the coccolithophorid *Emiliania huxleyi*, *Global Biogeochemical Cycles*, **19**(GB2023): doi:10.1029/2004GB002318.

Delworth, T. L. and T. R. Knutson (2000) Simulation of early 20th century global warming, *Science*, **287**: 2246-2250.

Delworth, T. L. and M. E. Mann (2000) Observed and simulated multidecadal variability in the Northern Hemisphere, *Climate Dynamics*, **16**: 661-676.

Dickson, R. R. (1999) All change in the Arctic, *Nature*, **397**: 389-391.

Dickson, R. R., R. Curry and I. Yashayaev (2003) Recent changes in the North Atlantic, *Philosophical Transactions of the Royal Society of London*, **361A**: 1917-1934.

Dickson, R. R., J. Meincke, S.-A. Malmberg and A. J. Lee (1988) The ``Great Salinity Anomaly'' in the northern North Atlantic 1968-1982, *Progress in Oceanography*, **20**: 103-151.

Duckworth, G., K. LePage and T. Farrell (2001) Low-frequency long-range propagation and reverbation in the central Arctic: Analysis of experimental results, *Journal of Acoustic Socierty of America*, **110**: 747-760.

Dyurgerov, M. B. and M. F. Meier (2000) Twentieth century climate change: Evidence from small glaciers, *PNAS*, **97**(4): 1406-1411.

Engel, A., I. Zondervan, K. Aerts, L. Beaufort, A. Benthien, L. Chou, B. Delille, J.-P. Gattuso, J. Harlay, C. Heemann, L. Hoffmann, S. Jacquet, J. Nejstgaard, M.-D. Pizay, E. Rochelle-Newall, U. Schneider, A. Terbrueggen and U. Riebesell (2005) Testing the direct effect of CO_2 concentration on a bloom of the coccolithophorid *Emiliania huxleyi* in mesocosm experiments, *Limnology and Oceanography*, **50**(2): 493-507.

Engelsen, O., E. N. Hegseth, H. Hop, E. Hansen and S. Falk-Petersen (2002) Spatial variability of chlorophyll-a in the Marginal Ice Zone of the Barents Sea, with relations to sea ice and oceanographic conditions, *Journal of Marine Systems*, **35**: 79-97.

Falk-Petersen, S., J. R. Sargent, J. Henderson, E. N. Hegseth, H. Hop and Y. B. Okolodkov (1998) Lipids and fatty acids in ice algae and phytoplankton from the marginal ice zone in the Barents Sea, *Polar Biology*, **20**: 41-47.

Falk-Petersen, S., J. R. Sargent, O. J. Lonne and S. Timofeev (1999) Functional biodiversity of lipids in Antarctic zooplankton: *Calanoides acutus*, *Calanus propinquus*, *Thysanoessa macrura* and *Euphausia crystallorophias*, *Polar Biology*, **21**(1): 37-47.

Fichefet, T., B. Tartinville and H. Goosse (2003) Antarctic sea ice variability during 1958-1999: A simulation with a global ice-ocean model, *Journal of Geophysical Research*, **108**(C3): 3102, doi:3110.1029/2001JC001148.

Frappart, F., G. Ramillien, S. Biancamaria, N. Mognard and A. Cazenave (2006) Evolution of high-latitude snow mass derived from the GRACE gravimetry mission (2002-2004), *Geophysical Research Letters*, **33**(L02501): doi:10.1029/2005GL024778.

Gavrilov, A. N. and P. N. Mikhalevsky (2002) Recent results of the ACOUS (Arctic Climate Observations using Underwater Sound) Program, *Acta Acustica united with Acustica*, **88**: 783-791.

Gavrilov, A. N., P. N. Mikhalevsky, V. V. Goncharov, Y. A. Chepurin and K. D. Sabinin (2005) Ocean acoustic thermometry, halinometry and sea ice measurements with an Arctic Ocean cabled observatory, *Conf. Underwater Acoustic Measurements*, Heraklion.

Geng, Q. and M. Sugi (2003) Possible Change of Extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols - study with a high-resolution AGCM, *Journal of Climate*, **16**: 2262-2274.

Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson and H. J. Zwally (1992) *Arctic and Antarctic Sea Ice, 1978-1987: satellite passive-microwave observations and analysis*, NASA SP-511, National Aeronautics and Space Administration, p.

Gradinger, R., C. Friedrich and M. Spindler (1999) Abundance, biomass and composition of the sea ice biota of the Greenland Sea pack ice, *Deep Sea Research*, **46**: 1457-1472.

Grebmeier, J. M. and P. Barry (1991) The influence of oceanographic processes on pelagic-benthic coupling in polar regions: a benthic perspective, *Journal of Marine Systems*, **2**: 495-518.

Grebmeier, J. M., W. O. Smith Jr and R. J. Conover (1995) Biological processes on Arctic continental shelves: ice-ocean biotic interactions. *Arctic oceanography: marginal ice zones and continental shelves*, W. O. Smith Jr and J. M. Grebmeier, Washinton DC, American Geophysical Union**:** 231-261.

Grippa, M., N. Mognard and T. Le Toan (2005) Comparison between the interannual variability of snow parameters derived from SSM/I and the Ob river discharge, *Remote Sensing of Environment*, **98**: 35-44.

Grippa, M., N. Mognard, T. Le Toan and E. G. Josberger (2004) Siberia snow depth climatology derived from SSM/I data using a combined dynamic and static algorithm, *Remote Sensing of Environment*, **93**(1-2): 30-41.

Hall, D. K., J. R. Key, K. A. Casey, G. A. Riggs and D. J. Cavalieri (2004) Sea ice surface temperature product from MODIS, *IEEE Transactions on Geoscience and Remote Sensing*, **42**: 1077-1087.

Hasselmann, K. (1976) Stochastic climate models. Part1: Theory, *Tellus*, **28**: 273-485.

Hatun, H., A. B. Sandø, H. Drange, B. Hansen and H. Valdimarsson (2005) Influence of the Atlantic Subpolar Gyre on the thermohaline circulation, *Science*, **309**: 1841-1844.

Hegseth, E. N. (1992) Sub-ice algal assemblages of the Barents Sea: species composition, chemical composition, and growth rates., *Polar Biology*, **12**: 485-496.

Hegseth, E. N. (1998) Primary production of the northern Barents Sea, *Polar Research*, **17**: 113-123.

Hobson, K. A., W. G. Ambrose and P. E. Renaud (1995) Sources of primary production, benthic-pelagic coupling and trophic relationships within the northeast water polynya: insights from d^{13} and $d^{15}N$ analysis, *Marine Ecology Progress Series*, **128**: 1-10.

Hurrell, J. W. (1995) Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, **269**: 676-679.

Hurrell, J. W., Y. Kushnir, G. Ottersen and M. Visbeck (2003) *The North Atlantic Oscillation: Climate Significance and Environmental Impact*. Washington DC, American Geophysical Union, p.

Haak, H., J. Jungclaus, U. Mikolajewicz and M. Latif (2003) Formation and propagation of great salinity anomalies, *Geophysical Research Letters*, **30**(9).

IPCC (2001) *Climate Change 2001: Third Assessment Report*, Cambridge University Press, p.

Johannessen, O. M. (1987) Summer marginal ice zone experiments during 1983 and 1984 in the Fram Strait and the Greenland Sea, *Journal of Geophysical Research*, **92**(C7): 6716-6718.

Johannessen, O. M., L. Bengtsson, M. W. Miles, S. I. Kuzmina, V. A. Semenov, G. V. Alekseev, A. P. Nagurnyi, V. F. Zakharov, L. P. Bobylev, L. H. Pettersson, K. Hasselmann and H. P. Cattle (2004) Arctic climate change - observed and modeled temperature and sea ice variability, *Tellus*, **56A**: 328-341.

Johannessen, O. M., W. J. Campbell, B. A. Farrelly, J. A. Johannessen, E. Svendsen, K. Kloster, I. Horjen, C. Matzler, J. Crawford, R. Harrington, L. Jones, C. Swift, V. E. Delnore, D. J. Cavalieri, P. Gloersen, S. V. Hsiao, O. H. Shemdin, T. W. Thomson and R. O. Ramseier (1983) Norwegian remote sensing experiment in a marginal ice zone, *Science*, **220**.

Johannessen, O. M., K. Khvorostovsky, M. W. Miles and L. P. Bobylev (2005) Recent ice-sheet growth in the interior of Greenland, *Science*, **310**: 1013-1016.

Johannessen, O. M., H. Sagen, T. Hamre, H. Hobæk, K. Hasselmann, E. Maier-Reimer, U. Mikolajewicz, P. Wadhams, A. Kaletzky, L. P. Bobylev, E. Evert, V.

Troyan, K. A. Naugolnykh and I. Esipov (1999a) Acoustic Monitoring of Ocean Climate in the Arctic (AMOC), *Operational Oceanography – at the European and regional scales, 2nd EuroGOOS International Conference*, Rome, Elsevier Oceanography Series.

Johannessen, O. M., E. V. Shalina and M. W. Miles (1999b) Satellite evidence for an Arctic sea ice cover in transformation, *Science*, **286**: 1937-1939.

Koberle, C. and R. Gerdes (2003) Mechanisms determining the variability of Arctic sea ice conditions and export, *Journal of Climate*, **16**: 2843-2858.

Kouraev, A. V., E. A. Zakharova, O. Samain, N. Mognard and A. Cazenave (2004) Ob' river discharge from TOPEX/Poseidon satellite altimetry data, *Remote Sensing of Environment*, **93**: 238-245.

Kristoffersen, Y. (1994). Utredning om anvendelse av luftpute fartøy til Arktisk forskning, Polarforskningskomiteen, Norges Forskningsråd**:** 38.

Kushner, P. J., I. M. Held and T. L. Delworth (2001) Southern Hemisphere atmospheric circulation response to global warming, *Journal of Climate*, **14**: 2238-2249.

Kuzmina, S. I., L. Bengtsson, O. M. Johannessen, H. Drange, L. P. Bobylev and M. W. Miles (2005) The North Atlantic Oscillation and greenhouse-gas forcing, *Geophysical Research Letters*, **32**(L04703): doi:10.1029/2004GL021064.

Kvingedal, B. (2005) Sea-Ice Extent and Variability in the Nordic Seas, 1967-2002. *The Nordic Seas: An Integrated Perspective*, H. Drange, T. M. F. Dokken, Tore, R. Gerdes and W. Berger, AGU, **158**.

Kwok, R., H. J. Zwally and D. Yi (2004) ICESat observations of Arctic sea ice: A first look, *Geophysical Research Letters*, **31**(L16401): doi:10.1029/2004GL02309.

Laxon, S. W., N. Peacock and D. Smith (2003) High interannual variability of sea ice thickness in the Arctic region, *Nature*, **425**: 947-950.

LePage, K. and H. Schmidt (1994) Modeling of low frequency transmission loss in the central Arctic, *Journal of Acoustic Socierty of America*, **96**: 1783-1795.

Lindsay, R. W. and J. Zhang (2005) The thinning of Arctic sea ice, 1988-2003: Have we passed a tipping point? *Journal of Climate*, **18**: 4879-4897.

Loptien, U. and E. Ruprecht (2005) Effect of synoptic systems on the variability of the North Atlantic Oscillation, *Monthly Weather Review*, **133**: 2894-2904.

Macdonald, R. W., T. Harner, J. C. Fyfe, H. Loeng and T. Weingartner (2003) *AMAP Assessment 2002: The Influence of Global Change on Contaminant Pathways to, within, and from the Arctic*. Oslo, Arctic Monitoring and Assessment Programe (AMAP), 65 p.

Maheu, C., A. Cazenave and C. R. Mechoso (2003) Water level fluctuation in La Plata basin (South America) from TOPEX/Poseidon satellite altimetry, *Geophysical Research Letters*, **30**(3): doi:10.1029/2002GL016033.

Markus, T. and D. J. Cavalieri (1998) Snow depth distribution over sea ice in the Southern Ocean from satellite passive microwave data. *Antarctic Sea Ice Physical*

Processes, Interactions and Variability, M. O. Jeffries, Washington, D.C., AGU, **74:** 19-40.

Matthiessen, J., M. Kutz-Pirrung and P. J. Mudie (2000) Freshwater chlorophycean algae in recent marine sediments of the Beaufort, Laptev and Kara Seas (Arctic Ocean) as indicators or river runoff, *International Journal of Earth Science*, **89**: 470-485.

Melnikov, I. A. (1997) *The Arctic sea ice ecosystem*. Amsterdam, Gordon and Breach Science Publishers, 204 p.

Mitchell, B. G., E. Brody, E. Yeh, C. McDain, J. C. Comiso and N. Maynard (1991) Meridional zonation of the Barents Sea ecosystem inferred from satellite remote sensing and in situ bio-optical observations, *Polar Research*, **10**: 147-162.

Mognard, N. M. and E. G. Josberger (2002) Northern Great Plains seasonal evolution of snowpack parameters from satellite passive microwave measurements, *Annals of Glaciology*, **34**: 15-23.

Morison, J., M. Steele and R. Andersen (1998) Hydrography of the upper Arctic Ocean measured from the nuclear submarine USS Pargo, *Deep Sea Research Part I: Oceanographic Research Papers*, **45**: 15-38.

Moritz, R. E., C. M. Bitz and E. J. Steig (2002) Dynamics of recent climate change in the Arctic, *Science*, **297**: 1497-1502.

Munk, W., P. F. Worcester and C. Wunsch (1995) *Ocean acoustic tomography*. New York, Cambridge University Press, p.

Munk, W. and C. Wunsch (1979) Ocean acoustic tomography: A scheme for large-scale monitoring, *Deep Sea Research*, **26A**: 123-161.

Mynemi, R. B., C. D. Keeling, C. J. Tucker, G. Asrar and R. R. Nemani (1997) Increased plant growth in the northern high latitudes from 1981 to 1991, *Nature*, **386**: 698-702.

Nagurnyi, A. P., V. G. Korostelev and P. A. Abaza (1994) Wave method for evaluating effective ice thickness of sea ice in climate monitoring, *Bull. Russian Acad. Sci. Phys. Suppl. Phys. Vib.*, **58**: 168-174.

Nansen, F. (1897) *Farthest North: Being the Record of a Voyage of Exploration of the Ship «Fram», 1893-1896, and of a Fifteen Months' Sleigh Journey by Dr. Nansen and Lt. Johansen*. New York, Harper, p.

Nørgaard-Pedersen, N., R. F. Spielhagen, H. Erlenheuser, P. M. Grootes, J. Heinemeier and J. Knies (2003) Arctic Ocean during the Last Glacial Maximum: Atlantic and polar domains of surface water mass distribution and ice cover, *Paleoceanography*, **18**(3): doi: 10.1029/2002PA000781.

Nørgaard-Pedersen, N., R. F. Spielhagen, J. Thiede and H. Kassens (1998) Central Arctic surface ocean environment during the past 80,000 years, *Paleoceanography*, **13**: 193-204.

Olsen, A., A. Omar, R. G. J. Bellerby, T. Johannessen and U. Ninneman (2006) Magnitude and origin of the anthropogenic carbon increase and 13C Suess effect in the Nordic Seas since 1981, *Global Biogeochemical Cycles*, (submitted).

Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G.-K. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M.-F. Weirig, Y. Yamanaka and A. Yool (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, **437**: 681-686.

Otterå, O. H. and H. Drange (2004) A possible coupling between Arctic fresh water, the Arctic sea ice cover and the North Atlantic Drift. A case study, *Advances in Atmospheric Sciences*, **21**: 784-801.

Otterå, O. H., H. Drange, M. Bentsen, N.-G. Kvamstø and D. Jiang (2004) Transient response of the Atlantic Meridional Overturning Circulation to enhanced freshwater input to the Nordic Seas-Arctic Ocean in the Bergen Climate Model, *Tellus*, **56A**: 342-361.

Otterå, O. H., H. Drange, M. Bentsen, N. G. Kvamstø and D. Jiang (2003) The sensitivity of the present-day Atlantic meridional overturning circulation to freshwater forcing, *Geophysical Research Letters*, **30**(17): 1898, doi:1810.1029/2003GL017578.

Overland, J. E. and M. Wang (2005a) The Arctic climate paradox: The recent decrease of the Arctic Oscillation, *Geophysical Research Letters*, **32**(L06701): doi:10.1029/2004GL021752.

Overland, J. E. and M. Wang (2005b) The third Arctic climate pattern: 1930s and early 2000s, *Geophysical Research Letters*, **32**(L20808): doi:10.1029/2005GL024254.

Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally and J. C. Comiso (1999) Arctic sea ice extents, areas, and trends, 1978-1996, *Journal of Geophysical Research*, **104**(C9): 20837-20856.

Petersen, G. H. and M. A. Curtis (1980) Differences in energy flow through major components of subarctic, temperate and tropical marine shelf ecosystems, *Dana*, **1**: 53.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vorosmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov and S. Rahmstorf (2002) Increasing river discharge to the Arctic Ocean, *Science*, **298**: 2171-2173.

Piepenburg, D. (2005) Recent research on Arctic benthos: common notions need to be revised, *Polar Biology*: doi:10.1007/s00300-00005-00013-00305.

Polyakova, Y. I. and R. Stein (2004) Holocene paleoenvironmental implications of diatom and organic carbon records from the southeastern Kara Sea (Siberian Margin), *Quaternary Research*, **62**(3): 256-266.

Pozdnyakov, D., A. Korosov and L. H. Pettersson (2004) New algorithm for natural water quality retrieval from spatial data, *Earth Obs Rem. Sens.*, **4**: 17-29.

Quadfasel, D. (2005) Oceanography: The Atlantic heat conveyor slows, *Nature*, **438**(7068): 565.

Ragner, C. L., Ed. (2001) *The 21st Century – Turning Point for the Northern Sea Route?* Dordrecht, the Netherlands, Kluwer Academic Publishers, p.

Rahmstorf, S. (1999) Shifting seas in the greenhouse, *Nature*, **399**: 523-524.

Raisanen, J. (2002) CO_2-induced changes in inter-annual temperature and precipitation variability in 19 CMIP2 experiments, *Journal of Climate*, **15**: 2395-2411.

Reichert, B. K., L. Bengtsson and J. Oerlemans (2002) Recent glacier retreat exceeds internal variability, *Journal of Climate*, **15**: 3069-3081.

Rey, F., H. R. Skjoldal and D. Slagstad (1987) Primary productioninrelationtoclimate changesinthe Barents Sea. *The effect of oceanographic conditions on distributionandpopulations dynamics of commercial fish stocksinthe Barents Sea*, H. Loeng, Bergen, Institute ofMarineResearch**:** 29-46.

Riggs, G. A., D. K. Hall and S. A. Ackerman (1999) Sea ice extent and classification mapping with the Moderate Resolution Imaging Spectroradiometer airborne simulator, *Remote Sensing of Environment*, **68**: 152-163.

Rignot, E. and P. Kanagaratnam (2006) Changes in the Velocity Structure of the Greenland Ice Sheet, *Science*, **311**(5763): 986-990.

Rignot, E. J., D. Braaten, S. P. Gogineni, W. B. Krabill and J. R. McConnell (2004) Rapid ice discharge from southeast Greenland glaciers, *Geophysical Research Letters*, **31**(L10401): doi:10.1029/2004GL019474.

Rignot, E. J. and R. H. Thomas (2002) Mass balance of polar ice sheets, *Science*, **297**: 1502-1506.

Risebrobakken, B., E. Jansen, C. Andersson, E. Mjelde and K. Hevrøy (2003) A high-resolution study of Holocene paleoclimatic and paleoceanographic changes in the Nordic Seas, *Paleoceanography*, **18**(1): doi:10.1029/2002PA000764.

Rothrock, D. A., Y. Yu and G. A. Maykut (1999) Thinning of the Arctic sea-ice cover, *Geophysical Research Letters*, **26**(23): 3469-3472.

Rowe, G. T., G. S. Boland, E. G. Escobar-Briones, M. E. Cruz-Kaegi, A. Newton, D. Piepenburg, I. Walsh and J. W. Deming (1997) Sediment community biomass and respiration in the Northeast Water polynya, Greenland: A numerical simulation of benthic lander and spade core data, *Journal of Marine Systems*, **10**: 483-496.

Rudels, B., L. G. Anderson and E. P. Jones (1996) Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean, *Journal of Geophysical Research*, **101**: 8807-8821.

Räisainen, J. (2001) CO_2-induced climate change in CMIP2 experiments. Quantification of agreement and role of internal variability, *Journal of Climate*, **14**: 2088-2104.

Sakshaug, E. (1991) Food webs and primary production in the Barents Sea, *NIPR Symposium on Polar Biology*.

Sakshaug, E. and H. R. Skjoldal (1989) Life at the ice edge, *Ambio*, **8**: 62-67.

Sakshaug, E. and D. Slagstad (1991) Light and productivity of phytoplankton in polar marine ecosystems: a physiological view, *Polar Research*, **10**: 69-86.

Sandven, S. and O. M. Johannessen (1990) Ice conditions in the Barents Sea during SIZEX89. *Ice Technology for polar oceans, computational mechanics publications*, T. K. S. Murthy, J. G. Paren, W. M. Sackinger and P. Wadhams**:** 309-320.

Sarnthein, M., S. van Kreveld, H. Erlenheuser, P. M. Grootes, M. Kucera, U. Pflaumann and M. Scholz (2003) Centennial-to-millenial-scale periodicities of Holocene climate and sediment injections off the western Barents shelf, 75°N, *Boreas*, **32**: 447-461.

Schneider, E. K., L. Bengtsson and Z.-Z. Hu (2003) Forcing of Northern Hemisphere climate trends, *Journal of the Atmospheric Sciences*, **60**: 1504-1521.

SEARCH (2001). SEARCH: Study of Environmental Arctic Change, Science Plan. Seattle, Polar Sciences Center, University of Washington.

Serreze, M. C., J. A. Maslanik, T. A. Scambos, F. Fetterer, J. Stroeve, K. Knowles, C. Fowler, S. D. Drobot, R. G. Barry and T. M. Haran (2003) A record minimum Arctic sea ice extent and area in 2002, *Geophysical Research Letters*, **30**(3): 1110, doi:1110.1029/2002GL016406.

Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. E. Osterkamp, M. B. Dyurgerov, V. E. Romanovsky, W. C. Oechel, J. Morison, T. Zhang and R. G. Barry (2000) Observational evidence for recent change in the northern high-latitude environment, *Climatic Change*, **46**: 159-206.

Shiklomanov, A. I., R. B. Lammers and C. J. Vorosmarty (2002) Widespread decline in hydrological monitoring threatens Pan-Arctic research, *EOS, Trans. Amer. Geophys. Union*, **83**(2): 13.

Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers, B. J. Peterson and C. J. Vorosmarty (2000) The dynamics of river water inflow to the Arctic Ocean. *The Freshwater Budget of the Arctic Ocean*, Dordrecht, The Netherlands, Kluwer Academic Publishers.

Skarsoulis, E. K., U. Send, G. Piperakis and P. Testor (2004) Acoustic thermometry of the western Mediterranean basin, *Journal of Acoustic Socierty of America*, **116**: 790-798.

Skjelvan, I., A. Olsen, L. G. Anderson, R. G. J. Bellerby, E. Falck, Y. Kasajima, C. Kivimae, A. Omar, F. Rey, A. Olsson, T. Johannessen and C. Heinze (2005) A Review of the Biogeochemistry of the Nordic Seas and Barents Sea – With Focus on the Inorganic Carbon Cycle. *Climate Variability in the Nordic Seas*, H. Drange, T. M. Dokken, T. Furevik, R. Gerdes and W. Berger, AGU, **158:** 157-176.

Slagstad, D. and S. Stokke (1994) Simulation of current fields, hydrography, ice cover and primary production in the northern Barents Sea, *Fisk. Hav.*, **9**: 1-46.

Slagstad, D. and K. Støle-Hansen (1991) Dynamics of plankton growth in the Barents Sea: model studies, *Polar Research*, **10**: 173-186.

Soltwedel, T., E. Bauerfeind, M. Bergmann, N. Budeava, E. Hoste, N. Jaeckisch, K. v. Juterzenka, J. Matthiessen, V. Mokievsky, E.-M. Nothig, N. Queric, B.

Sablotny, E. Sauter, I. Schewe, B. Urban-Malinga, J. Wegner, M. Wlodarska-Kowalczuk and M. Klages (2005) HAUSGARTEN: multidisciplinary investigations at a deep-sea, long-term observatory in the Arctic Ocean, *Oceanography*, **18**(3): 46-61.

Sorteberg, A., T. Furevik, H. Drange and N.-G. Kvamstø (2005) Effects of simulated natural variability on Arctic temperature projections, *Geophysical Research Letters*, **32**(L18708): doi:10.1029/2005GL023404.

Spindler, M. (1994) Notes on the biology of the sea ice zones in the Arctic and Antarctic, *Polar Biology*, **14**: 319-324.

Stabeno, P. J. and J. E. Overland (2001) Bering Sea shifts toward an earlier spring transition, *EOS*, **82**: 317,321.

Steele, J. H. (1991) Marine functional diversity, *BioSciences*, **41**: 470-474.

Stein, R., K. Dittmers, K. Fahl, M. Kraus, J. Matthiessen, F. Niessen, M. Pirrung, Y. I. Polyakova, F. Schoster, T. Steinke and D. K. Futterer (2004) Arctic (palaeo) river discharge and environmental change: evidence from the Holocene Kara Sea sedimentary record, *Quaternary Science Reviews*, **23**: 1485-1511.

Stenseth, N. C., A. Mysterud, G. Ottersen, J. W. Hurrell, K.-S. Chan and M. Lima (2002) Ecological effects of climate fluctuations, *Science*, **297**: 1292-1296.

Stouffer, R. J., J. Yin, J. M. Gregory, K. W. Dixon, M. J. Spelman, W. Hurlin, A. J. Weaver, M. Eby, G. M. Flato, H. Hasumi, A. Hu, J. H. Jungclaus, I. V. Kamenkovich, A. Levermann, M. Montoya, S. Murakami, S. Nawrath, A. Oka, W. R. Peltier, D. Y. Robitaille, A. Sokolov, G. Vettoretti and S. L. Weber (2006) Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *Journal of Climate*, (submitted).

Swift, J. H., K. Aagaard, L. Tomikhov and E. G. Nikiforov (2005) Long-term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set, *Journal of Geophysical Research*, **110**(C03012): doi:10.1029/2004JC002312.

Syvertsen, E. E. (1991) Ice algae in the Barents Sea: types of assemblages, origin, fate and role in the ice-edge phytoplankton bloom, *Polar Research*, **10**: 277-287.

Thiede, J., D. Bauch, H. Erlenheuser, G. Winckler and G. Pavlova (2002) Carbon isotopes and habitat of polar planktic foraminifera in the Okhotsk Sea: the "carbonate ion effect" under natural conditions, *Marine Micropaleontology*, **45**(2): 83-99.

Thiede, J. and H. A. Bauch (1999) The Late Quaternary history of northern Eurasia and the adjacent Arctic Ocean: An introduction to QUEEN, *Boreas*, **8**(1): 3-5.

Thiede, J., H. A. Bauch, C. Hjort and J. Mangerud (2001a) The late Quaternary stratigraphy and environments of northern Eurasia and the adjacent Arctic seas – new contributions from QUEEN, *Global and Planetary Change*, **31**(1-4): 1-474.

Thiede, J., P. Schafer, W. Ritzau, M. Schluter and A. Schroder-Ritzrau (2001b) Present and past oceanographic controls of sediment formation in the North Atlantic – Arctic Gateway. *The Northern North Atlantic*, P. Schafer, W. Ritzrau, M. Schluter and J. Thiede, Berlin, Springer Verlag**:** 463-491.

Thomas, R. H., T. Akins, B. Csatho, M. Fahnestock, S. P. Gogineni, C. Kim and J. Sonntag (2000) Mass balance of the Greenland ice sheet at high elevations, *Science*, **289**: 426-428.

Vinje, T. (2001) Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic Seas during the period 1864-1998, *Journal of Climate*, **14**(3): 255-267.

Wadhams, P. and N. R. Davis (2000) Further evidence of ice thinning in the Arctic Ocean, *Geophysical Research Letters*, **27**(24): 3973-3975.

Walsh, J. J., D. A. Dieterle, W. Maslowski, J. M. Grebmeier, T. E. Whitledge, M. Flint, I. N. Sukhanova, N. Bates, G. F. Cota and D. Stockwell (2005) A numerical model of seasonal primary production within the Chukchi/Beaufort Seas, *Deep Sea Research Part II: Topical Studies in Oceanography*, **52**(24-26): 3541.

Wang, G. and L. You (2004) Delayed impact of the North Atlantic Oscillation on biosphere productivity in Asia, *Geophysical Research Letters*, **31**(L12210): doi:10.1029/2994GL019766.

Wassmann, P., I. Andreassen, M. Reigstad and D. Slagstad (1996) Pelagic-benthic coupling in the Nordic Seas: The role of episodic events, *Marine Ecology*, **17**: 447-471.

Wassmann, P. and D. Slagstad (1993) Seasonal and annual dynamics of particulate carbon flux in the Barents Sea, *Polar Biology*, **13**: 363-372.

Wassmann, P., D. Slagstad, C. W. Riser and M. Reigstad (2006) Modelling the ecosystem dynamics of the Barents Sea including the marginal ice zone II. Carbon flux and interannual variability, *Journal of Marine Systems*, **59**(1-2): 1-24.

Werner, I. and R. Gradinger (2002) Under-ice amphipods in the Greenland Sea and Fram Strait (Arctic): environmental controls and seasonal patterns below the pack ice, *Marine Biology*, **140**: 317-326.

Wilkinson, D. and S. Bacon (2005) The spatial and temporal variability of the East Greenland Coastal Current from historic data, *Geophysical Research Letters*, **32**(L24618): doi:10.1029/2005GL024232.

Worcester, P. F. and R. C. Spindel (2005) North Pacific Acoutic Laboratory, *Journal of Acoustic Socierty of America*, **1499-1510**.

Yu, Y., G. A. Maykut and D. A. Rothrock (2004) Changes in the thickness distribution of Arctic sea ice between 1958-1970 and 1993-1997, *Journal of Geophysical Research*, **109**(C08004): doi:10.1029/2003JC001982.

Zwally, H. J., A. C. Brenner, J. A. Major, R. Bindschadler and J. G. Marsh (1989) Growth of Greenland Ice Sheet: Measurement, *Science*, **246**: 1587-1589.

Zwally, H. J., M. B. Giovinetto, J. Li, H. G. Cornejo, M. A. Beckley, A. C. Brenner, J. L. Saba and D. Yi (2005) Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992-2002, *Journal of Glaciology*, **51**(175): 509-527.

Appendix A: List of partners in IPY-CARE

1. **NERSC** (Nansen Environmental and Remote Sensing Center) Norway
2. **AWI** (Alfred-Wegener Institute for Polar and Marine Research) Germany
3. **MPIfMet** (Max-Planck Institute for Meteorology) Germany
4. **IPOE/ASM** (Christian-Albrechts-Universität zu Kiel/Academy of Sciences Mainz) Germany
5. **UPMC/LODYC** (Université Pierre et Marie Curie) France
6. **ASM/GEOMAR** (Academy of Science Mainz/GEOMAR Research Center) Germany
7. **UGOT** (Göteborg University) Sweden
8. **FIMR** (Finnish Institute of Marine Research) Finland
9. **NPI** (Norwegian Polar Institute) Norway
10. **SRC AARI** (Arctic and Antarctic Research Institute) Russia
11. **UCL-ASTR** (Université Catholique de Louvain) Belgium
12. **Univbris** (Bristol Glaciology Centre) UK
13. **UiO** (University of Oslo) Norway
14. **SMHI** (Swedish Meteorological and Hydrological Institute) Sweden
15. **DMI** (Danish Meteorological Institute) Denmark
16. **VEXCEL UK** (Vexcel UK Limited) UK
17. **MGO** (Voikov Main Geophysical Observatory) Russia
18. **NIERSC** (Nansen International Environmental and Remote Sensing Center) Russia
19. **APN** (Akvaplan-Niva) Norway
20. **Uni-Ham** (University of Hamburg) Germany
21. **NCFS** (Norwegian College of Fishery Science) Norway
22. **BCCR** (Bjerknes Centre for Climate Researc) Norway
23. **ULB** (Université Libre de Bruxelles) Belgium
24. **ICTA-UAB** (Institute de Cienca i Tecnologia Ambientals, Uni. Autonoma de Barcelona) Spain
25. **UoT** (University of Tromsø) Norway
26. **met.no** (Meteorologisk Institutt) Norway
27. **IMR** (Institute of Marine Science) Norway
28. **IOPAN** (Institute of Oceanology, Polish Academy of Science) Poland
29. **POL** (Natural Environment Research Council) UK
30. **UoP** (University of Plymouth) UK
31. **UCAM-DAM** (Department of Applied Mathematics and Theoretical Physics, Uni. of Cambridge) UK
32. **BC** (Brockmann Consult) Germany
33. **UB** (Bremen University) Germany
34. **IFREMER** (Institut Français de Recherche pour l'Exploitation de la Mer) France
35. **UCL** (University College London) UK
36. **UAAR** (University of Aarhus) Denmark
37. **GEUS** (Geological Survey of Denmark and Greenland) Denmark
38. **UOL** (Arctic Centre University of Lapland) Finland
39. **LEGOS** (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales) France
40. **MSI** (Martec Serpe IESM)
41. **IGRAS** (Institute of Geography Russia Academy of Science) Russia
42. **NTSOMZ** (Research Center for Earth Operative Monitoring) Russia
43. **ORCA** (ORCA Instruments) France
44. **ICES** (International Council for the Exploration of the Sea) Denmark
45. **UU**(University of Uppsala) Sweden
46. **MRI** (Marine Research Institute) Iceland
47. **NWPI** (Northern Water Problems Institute) Russia
48. **PINRO** (Knipovich Polar Research Institute of Marine Fisheries and Oceanography) Russia
49. **SP** (Sami Parliament in Finland) Finland
50. **TO** (Terra Orbit) Norway
51. **SPEED** (Carl von Ossietzky University of Oldenburg) Germany
52. **OASYS** (O.A. Sys. Ocean Atmosphere Systems) Germany

53. **SINTEF** (SINTEF) Norway
54. **ESARC** (Environmental Systems Analysis Research Center) USA
55. **INMH** (National Institute of Meteorology and Hydrology) Romania
56. **IARC** (International Arctic Research Center, University of Alaska) USA
57. **APL/UW** (Applied Physics Laboratory, University of Washington) USA
58. **PMEL/NOAA** (Pacific Marine Environmental Laboratory) USA
59. **COLA** (Center for Ocean-Land-Atmosphere Studies) USA
60. **IAP** (Institute of Atmospheric Physics, Chinese Academy of Science) China
61. **ZIN** (Zoological Institute, Russian Academy of Science) Russia
62. **RUG** (Groningen University) Netherland
63. **UWB** (Bangor University Wales) UK
64. **GFI** (Geophysical Institute, University of Bergen) Norway
65. **GEO** (Department of Earth Sciences, University of Bergen) Norway
66. **SNF** (Institute for Research in Economics and Business Administration) Norway
67. **UNIS** (University Centre in Svalbard) Norway
68. **NILU** (Norwegian Institute for Air Research), Norway
69. **UNIVISJON** (University of Bergen) Norway
70. **SIO (**Shirshov Institute of Oceanology, Russian Academy of Sciences) Russia
71. **MMBI** (Murmansk Marine Biological Institute) Russia
72. **SPBU** (St. Petersburg State University) Russia
73. **UWAS** (University of Washington) USA
74. **NOAA** (Arctic Research Office) USA
75. **UCAM** (University of Cambridge) UK
76. **LDEO** (Lamont-Doherty Earth Observatory) USA
77. **IPF** (International Polar Foundation) Belgium
78. **IACM-FORTH** (Institute of Applied and Computational Mathematics, Foundation for Research and Technology) Crete
79. **NZC** (Nansen-Zhu International Research Centre) China
80. **Scripps** (Scripps Institution of Oceanography) USA
81. **NCU** (Department of Climatology**,** Nicholas Copernicus University) Poland
82. **FMI** (Finnish Meteorological Institute)Finland
83. **UH** (University of Helsinki) Finland
84. **SAMS** (Scottish Association for Marine Science) UK